Kan vi få et bedre miljø med smartere kloakker?

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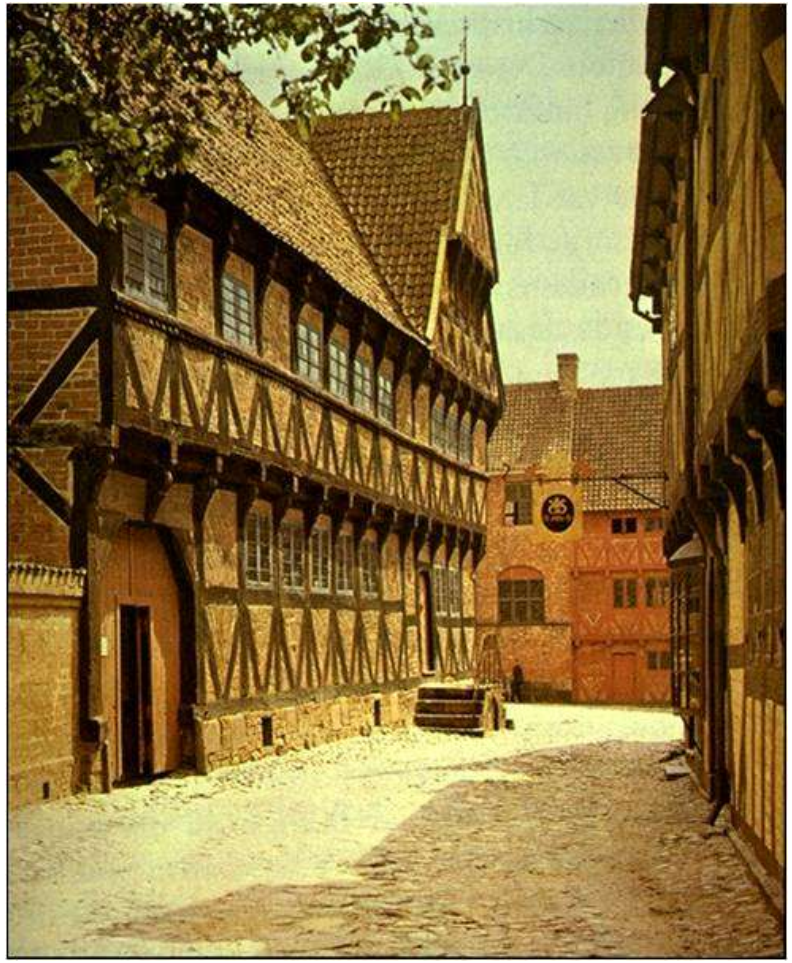
Kan vi få et bedre miljø med smartere kloakker?

Lidt om mig

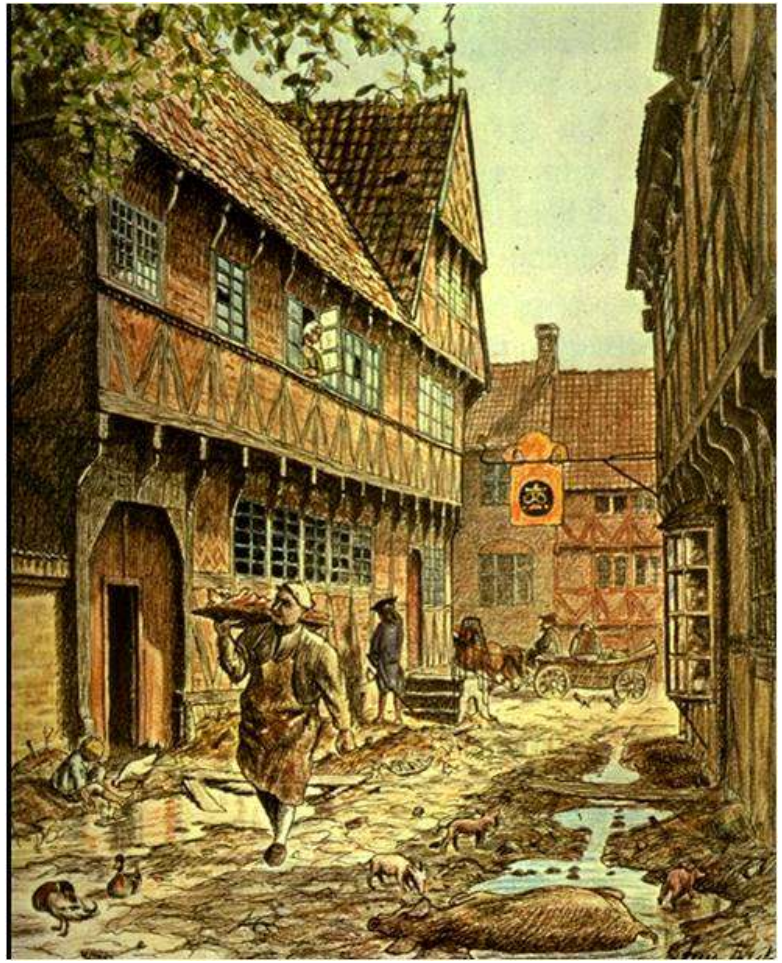
- Født i Padova, tæt på Venedig
- Uddannet som miljøingeniør
- Kom til Danmark som udvekslingsstudent i 2005
- PhD om modellering af miljøfremmede stoffer i regnvand (2011)
- Arbejder på DTU Miljø med styring og modellering af afløbssystemer
- Deltid ansat hos Krüger Veolia A/S (jeg tager forskning ud i ”den virkelige verden”)

Why do we have sewers?

Aarhus ”gamle by” – a living museum

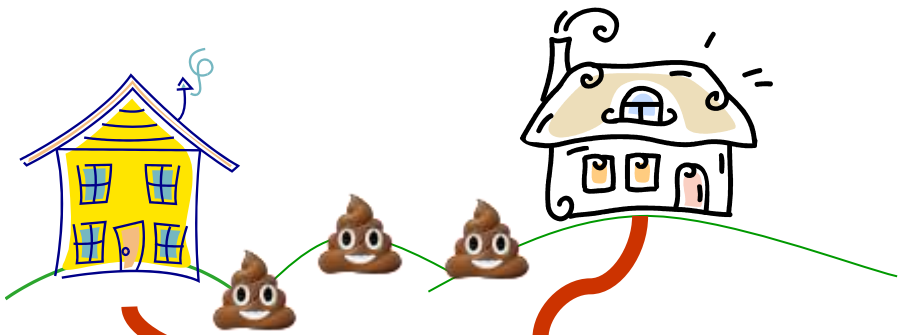


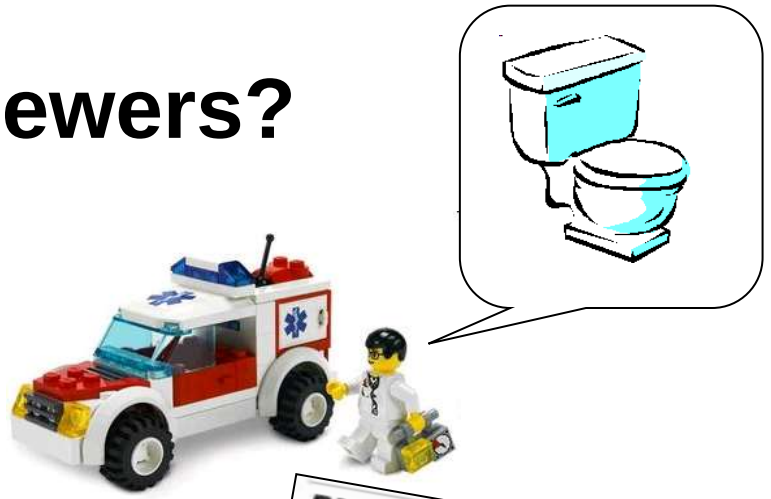
Today



Around 1850

Why do we have sewers?





Before 1800

(Western Cities)

BMJ readers choose sanitation as greatest medical advance since 1840

Annabel Ferriman BMJ

More than 11 300 readers of the *BMJ* chose the introduction of clean water and sewage disposal—"the sanitary revolution"—as the most important medical milestone since 1840, when the *BMJ* was first published. Readers were given 10 days to vote on a shortlist of 15 milestones, and sanitation topped the poll, followed closely by the discovery of antibiotics and the development of anaesthesia.

The work of the 19th century lawyer Edwin Chadwick, who pioneered the introduction of piped water to people's homes and sewers rinsed by water, attracted 15.8% of the votes, while antibiotics took 15%, and anaesthesia took 14%. The next two most popular were the introduction of vaccines, with 12%, and the discovery of the structure of DNA (9%).

A total of 11 341 people voted on the shortlist, which was chosen by a panel of experts from a list nominated by readers. Almost a third of the voters were doctors, while a fifth were members of the general public, and one in seven were students. Another tenth were academic researchers. Almost two fifths of the voters were from the United Kingdom, and a fifth were from the United States.

Johan Mackenbach, professor of public health at Erasmus MC Medical Center, Rotterdam, who championed the cause of sanitation, said, "I'm delighted that sanitation is recognised by so many people as such an important milestone. The general lesson which still holds is that passive protection against health hazards is often the best way to improve population health.

"The original champions of the sanitary revolution were John Snow, who showed that cholera was spread by water, and Edwin Chadwick, who came up with the idea of sewage disposal and piping water into homes.

"Inadequate sanitation is still a major problem in the developing world."

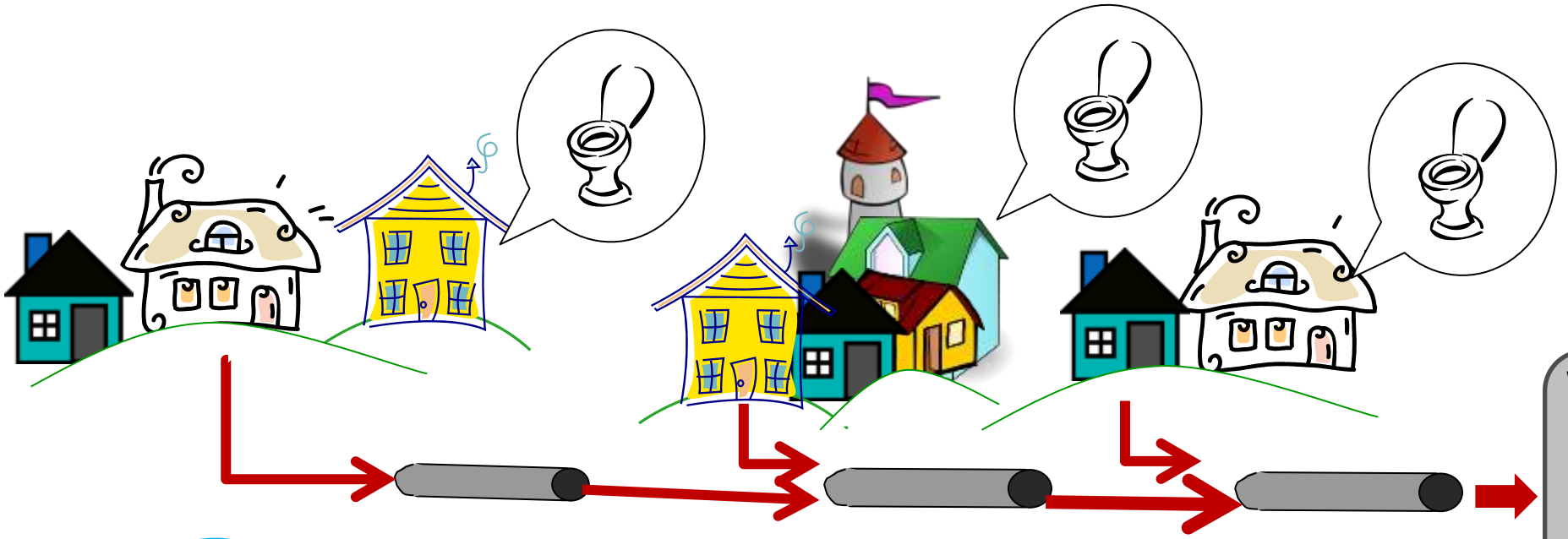
The *Medical Milestones* supplement is distributed with this week's *BMJ*.

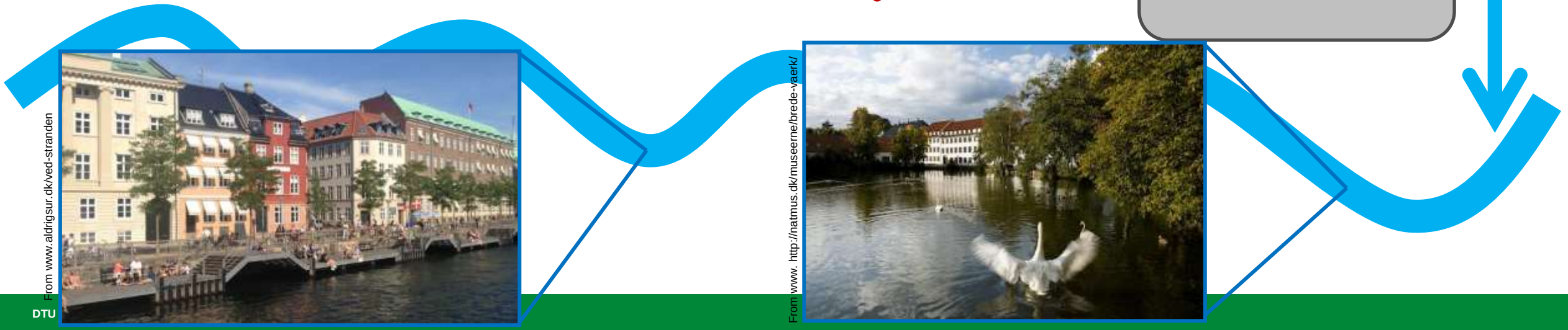
BMJ | 20 JANUARY 2007 | VOLUME 334

m

Ferriman, A. 2007. "BMJ Readers Choose the 'Sanitary Revolution' as Greatest Medical Advance since 1840." Bmj 334 (7585): 111–11. doi:10.1136/bmj.39097.611806.DB.

Our cities when sun is shining…

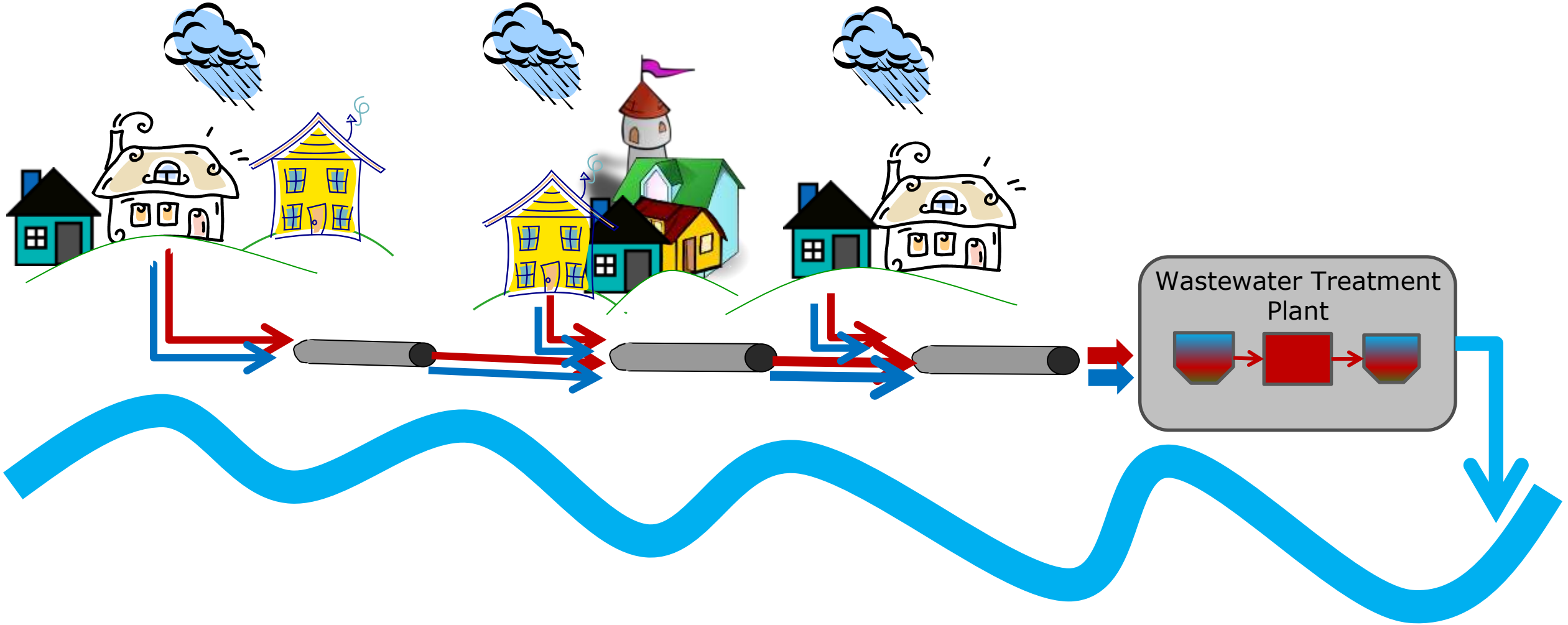




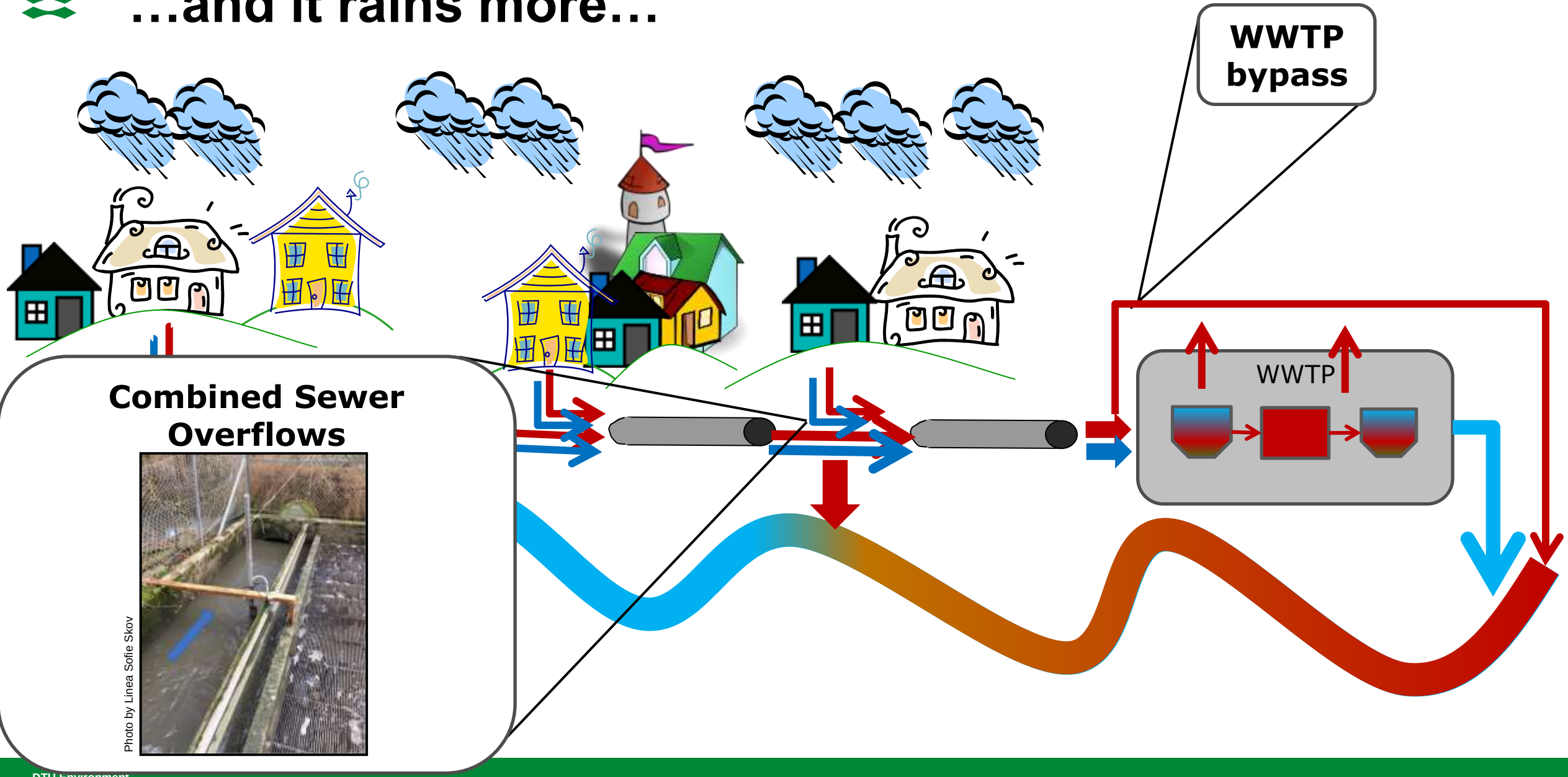
From www.aldrigsur.dk/ved-stranden

From www. http://natmus.dk/museerne/brede-vaerk/

…but sometimes it rains…



…and it rains more…

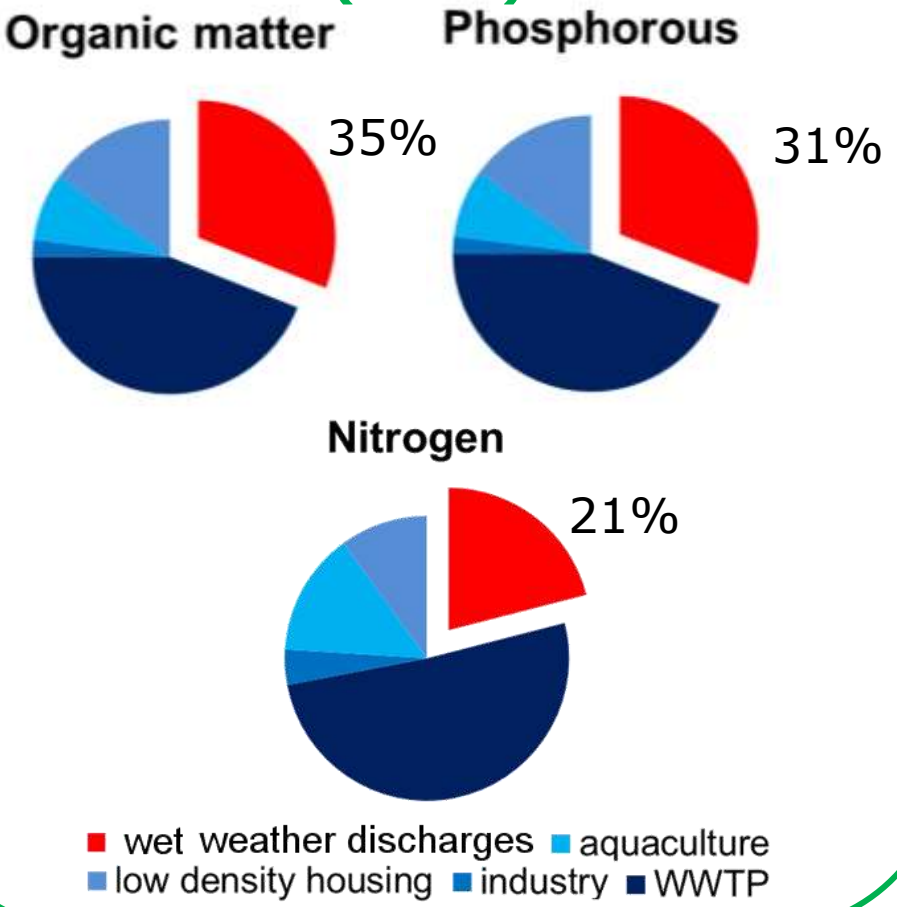


…and it rains more…

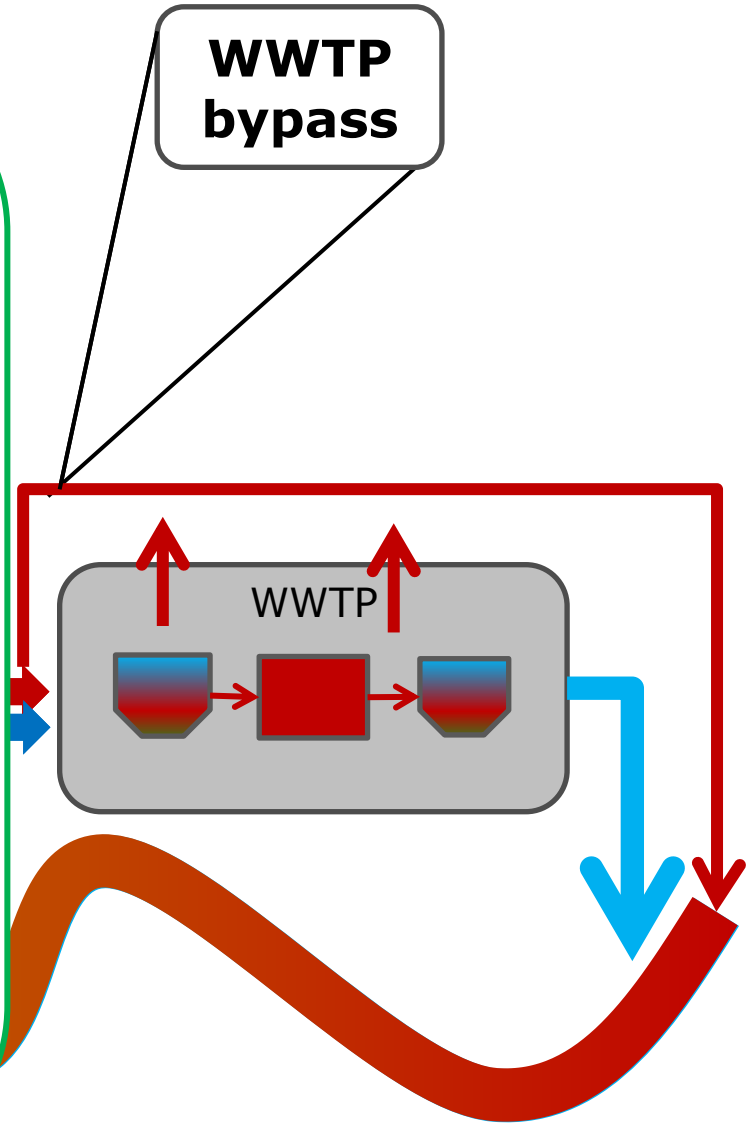
Combined Sewer Overflows

Photo by Linea Sofie Skov

Pollutant contribution from point discharges in DK (2015)



Source: Miljø- og Fødevareministeriet Styrelsen for Vand- og Naturforvaltning (2017). Punktkilder 2015



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Combined Sewer Overflows

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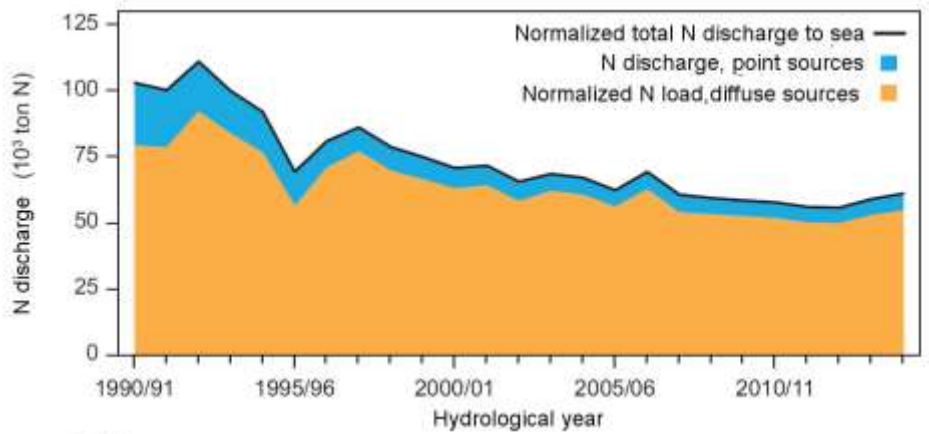
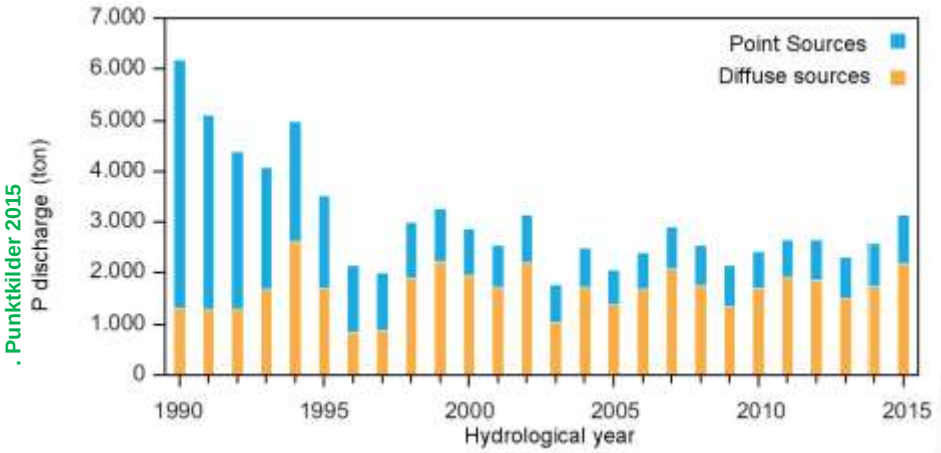


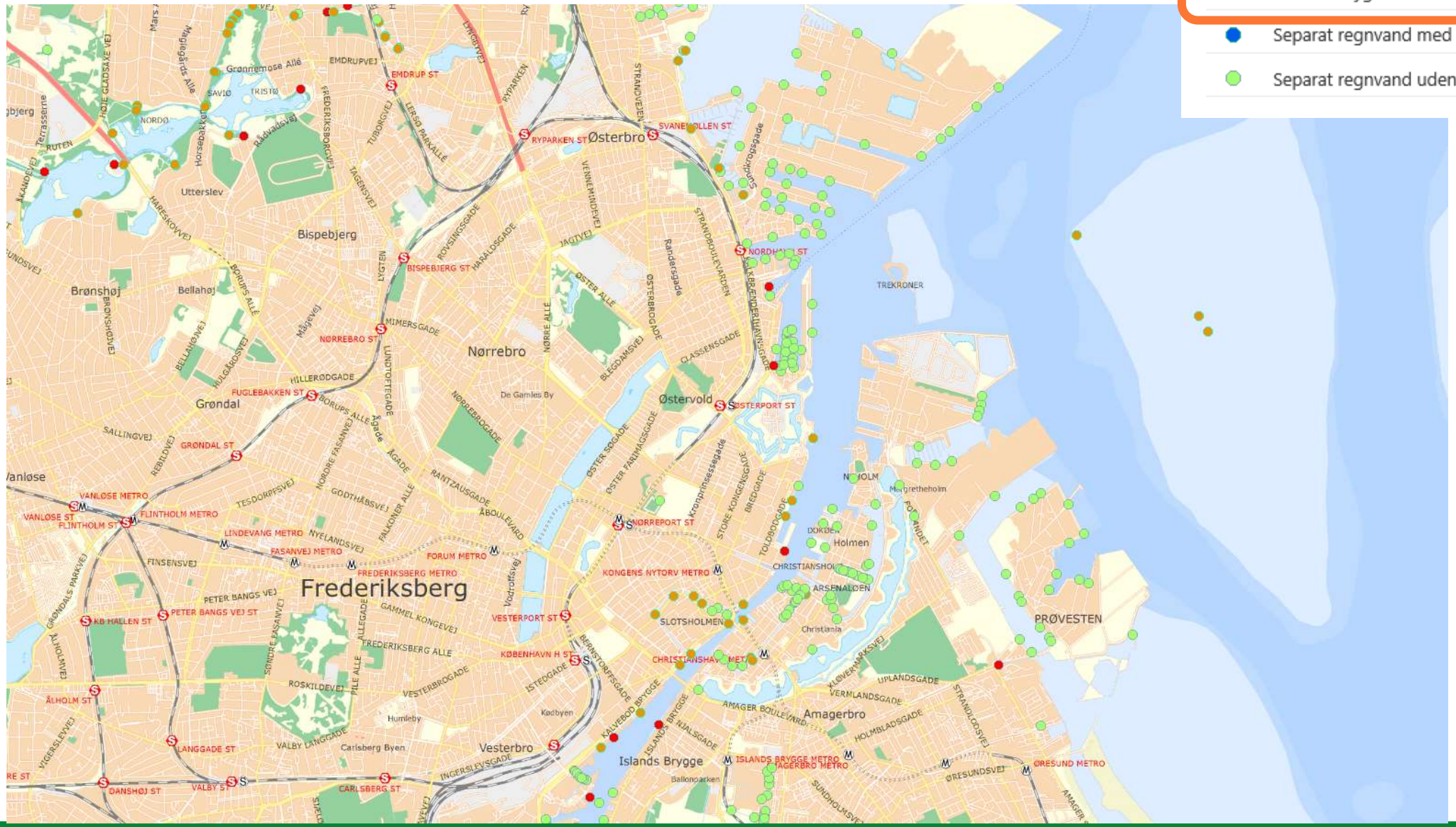


Source: Miljø- og Fødevareministeriet Styrelsen for Vand- og Naturforvaltning (2017)
. Punktkilder 2015

WWTP bypass

Kløakoverløb er overalt

over 5,000 i hele Danmark



Source: Danmarks Miljøportal (www.miljoeportal.dk)

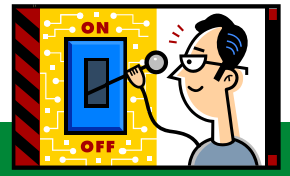
Intermittent discharges – which problems they can cause?

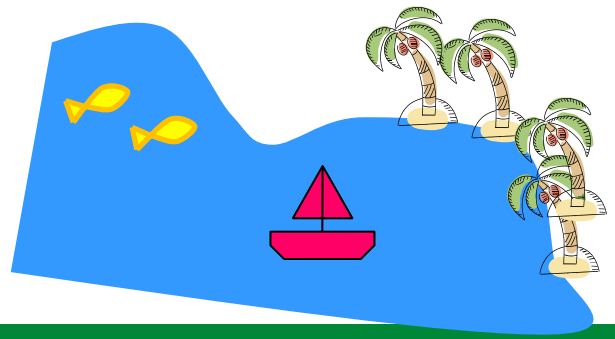
Effect	Description	Type of effect
Physical changes	Flooding in urban and rural areas Erosion Resuspension of sediments	Acute (short time scale)
Aesthetical pollution	Toilet paper, condoms, cotton buds, etc. hanging or settled on beaches	
Hygienic pollution	Diseases for humans Diseases for animals	
Physical-chemical changes in the river	Oxygen depletion High concentration of ammonia	
Eutrophication	Organic pollutants (BOD, COD) Nutrients (N, P)	Accumulative (long time scale)
Changes in ecological status	-	
Toxic and/or xenobiotics	Toxicity (acute and chronic) Persistence Bioaccumulation	Acute/Accumulative

Arnbjerg-Nielsen, K., Johansen, N.B., 2002. Krav til regnbetingede udledninger i forhold til Vandrammedirektivet, Rapport, Spildevandskomiteen. (https://ida.dk/sites/prod.ida.dk/files/krav_til_regnbetingede_udledninger_i_forhold_til_vandrammedirektivet_2002.pdf, tilgået 16/11/2017)

Once upon a time in Denmark

The good old operator

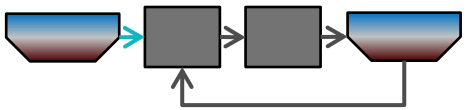




WWTP overloading CSO

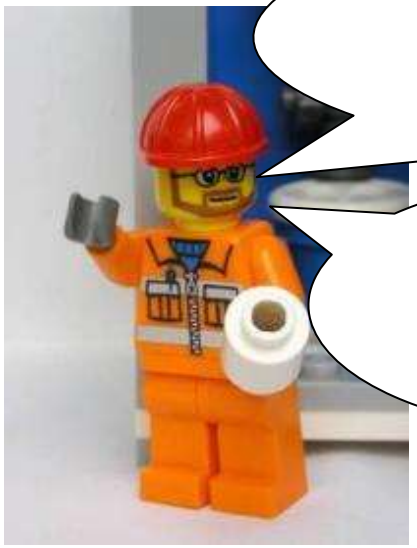
Increased demand for recreational use

flooding



Energy optimization

Once upon a time in Denmark



I need to optimize the performance of my system

(without building a lot of new expensive things)

Smart people from university, please help me!

The good old operator

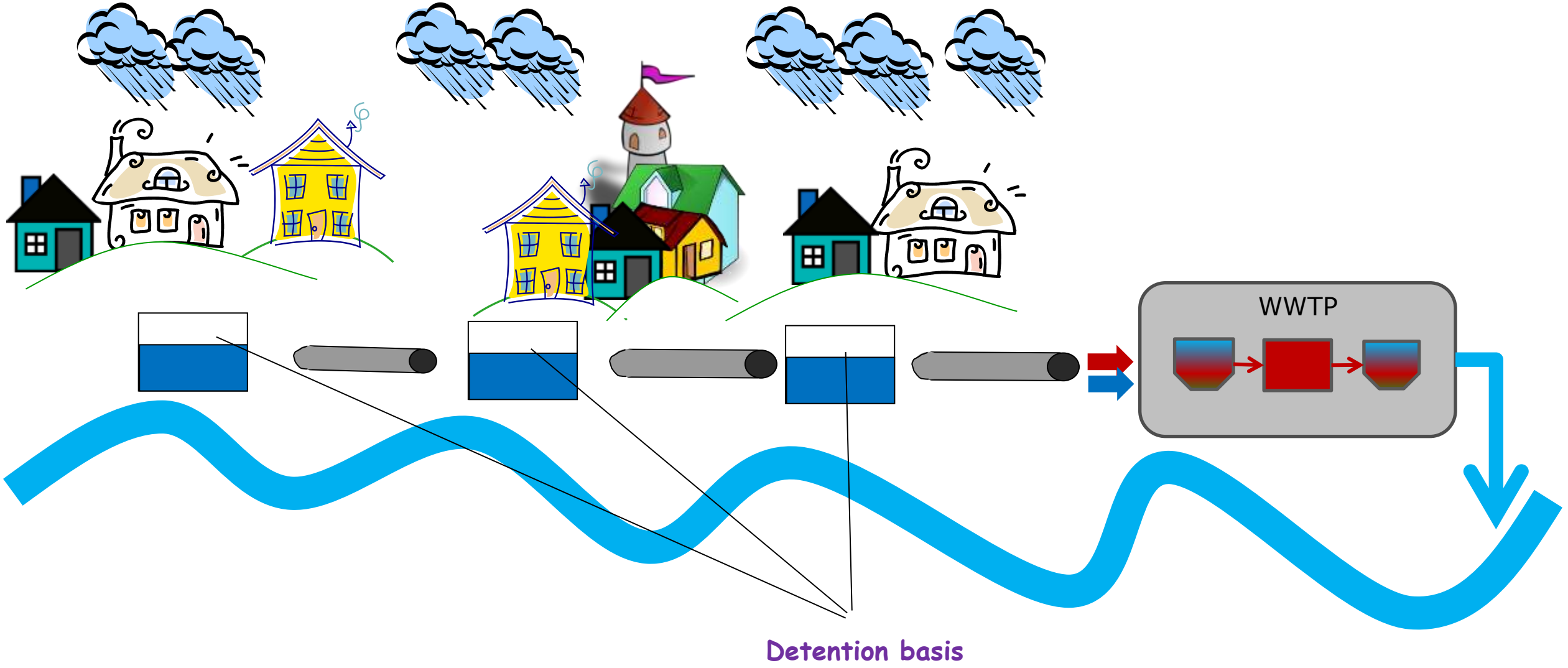
From lego.wikia.com

2007-now … a range of activities

Universities + research institutions + water utilities + consultants

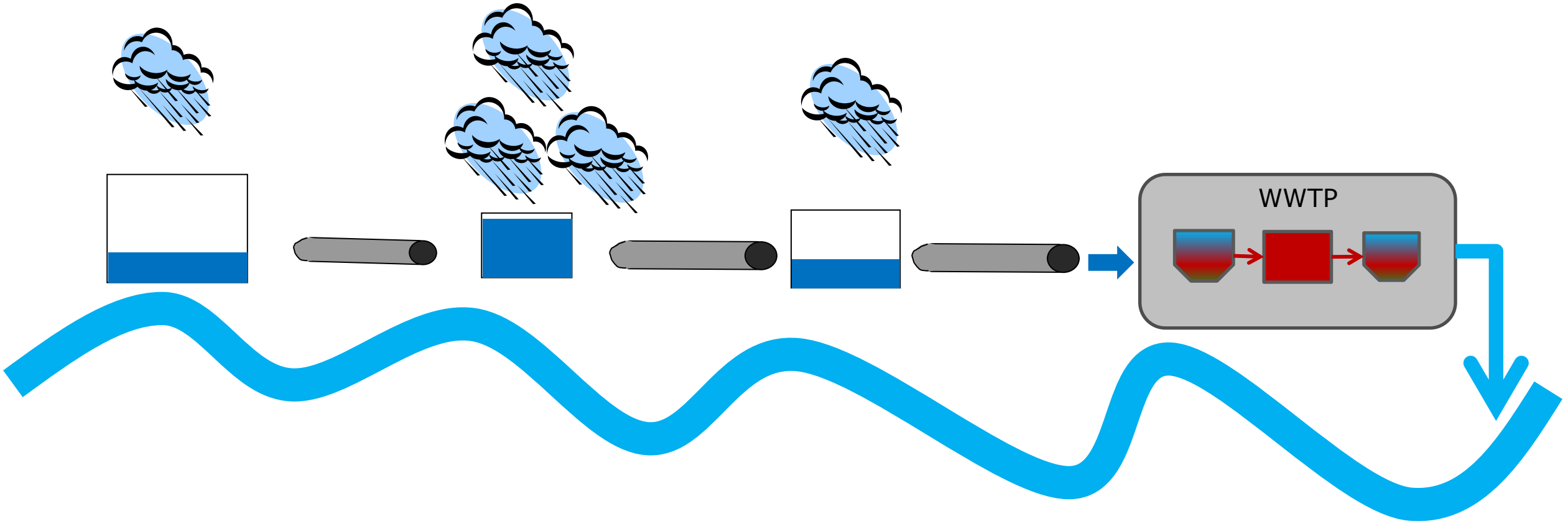
- Many projects
  - Storm- and Wastewater Informatics (SWI)
  - Klimaspring
  - Prepared
  - AMOK
  - Water Smart Cities
- Industrial PhDs
- Industrial postdocs
- Many MSc theses

One option to avoid overflow…



Real Time Control of drainage network

- Rain is not uniform → we can optimize the storage across the system → less overflow
- WWTP doesn't like high flows → we can regulate the inlet flow to the WWTP → less bypass



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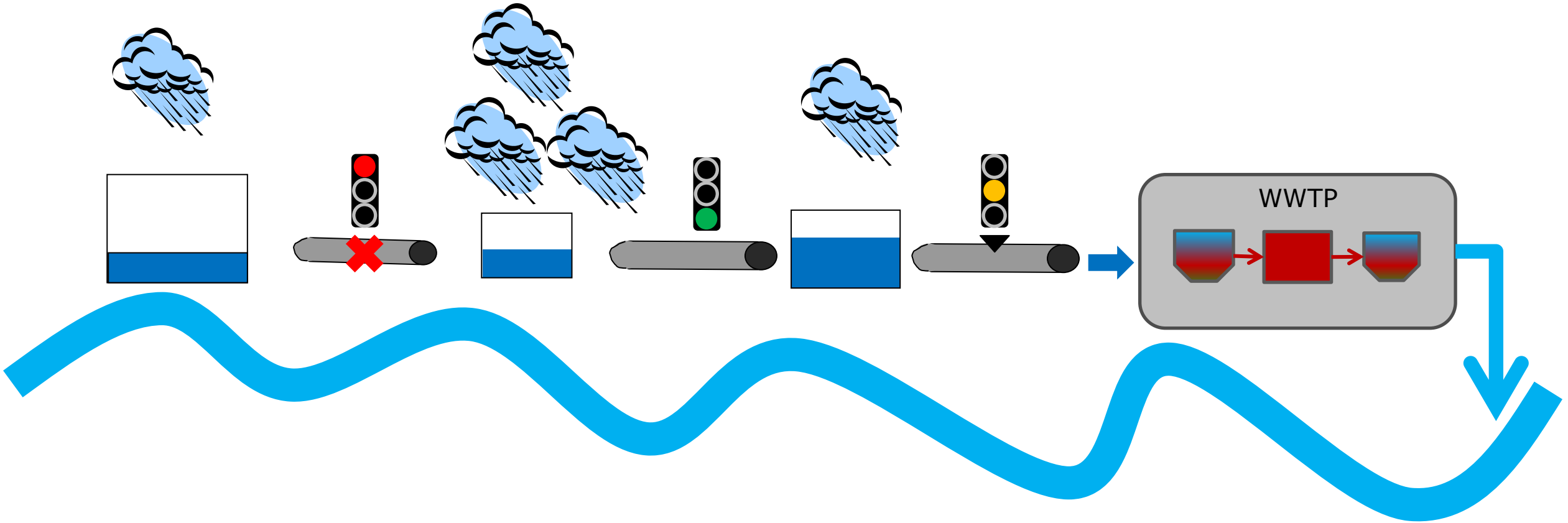
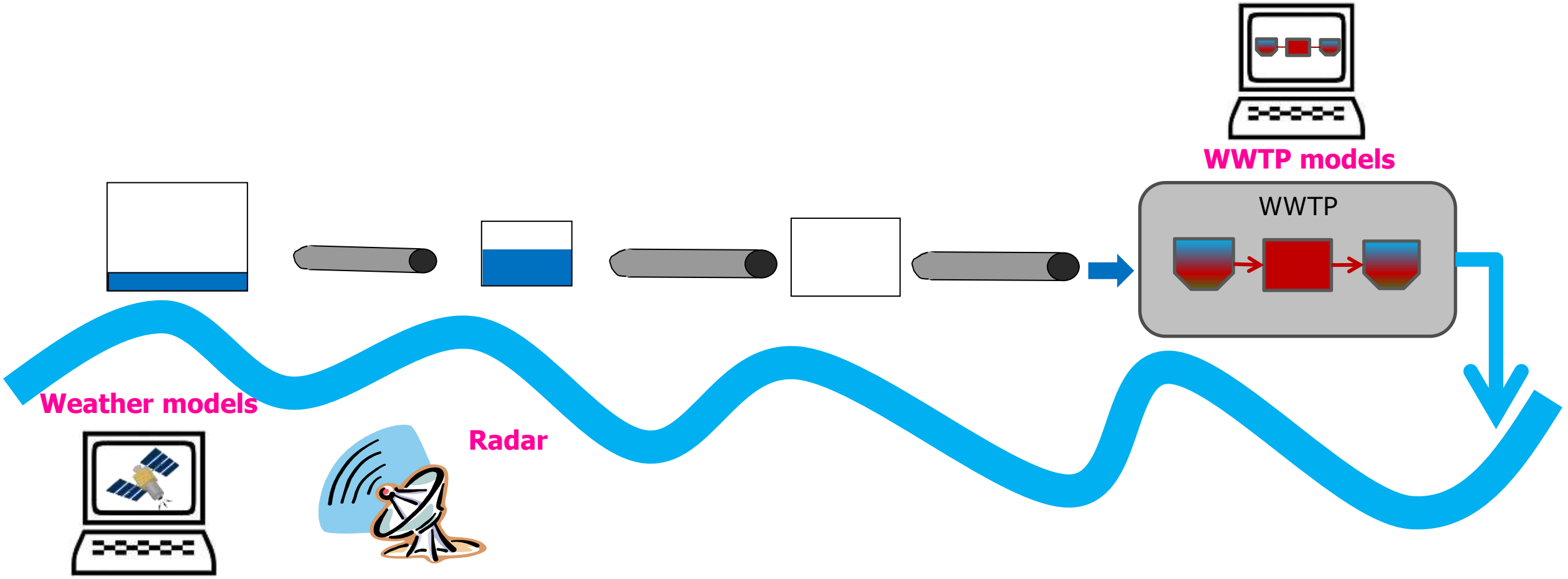


Model Predictive Control

- We can forecast rainfall → where and how much is going to rain → even less CSO
- We can forecast WWTP status → how much water the WWTP can treat → even less bypass



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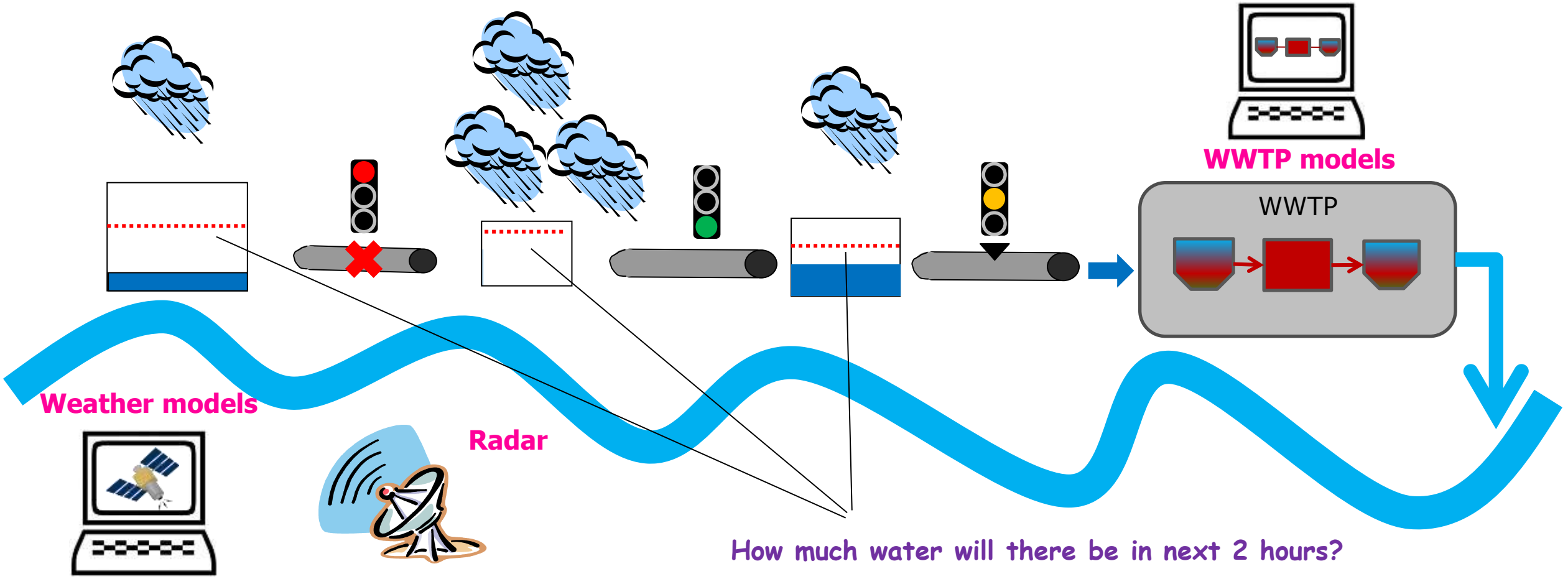


Our new concept

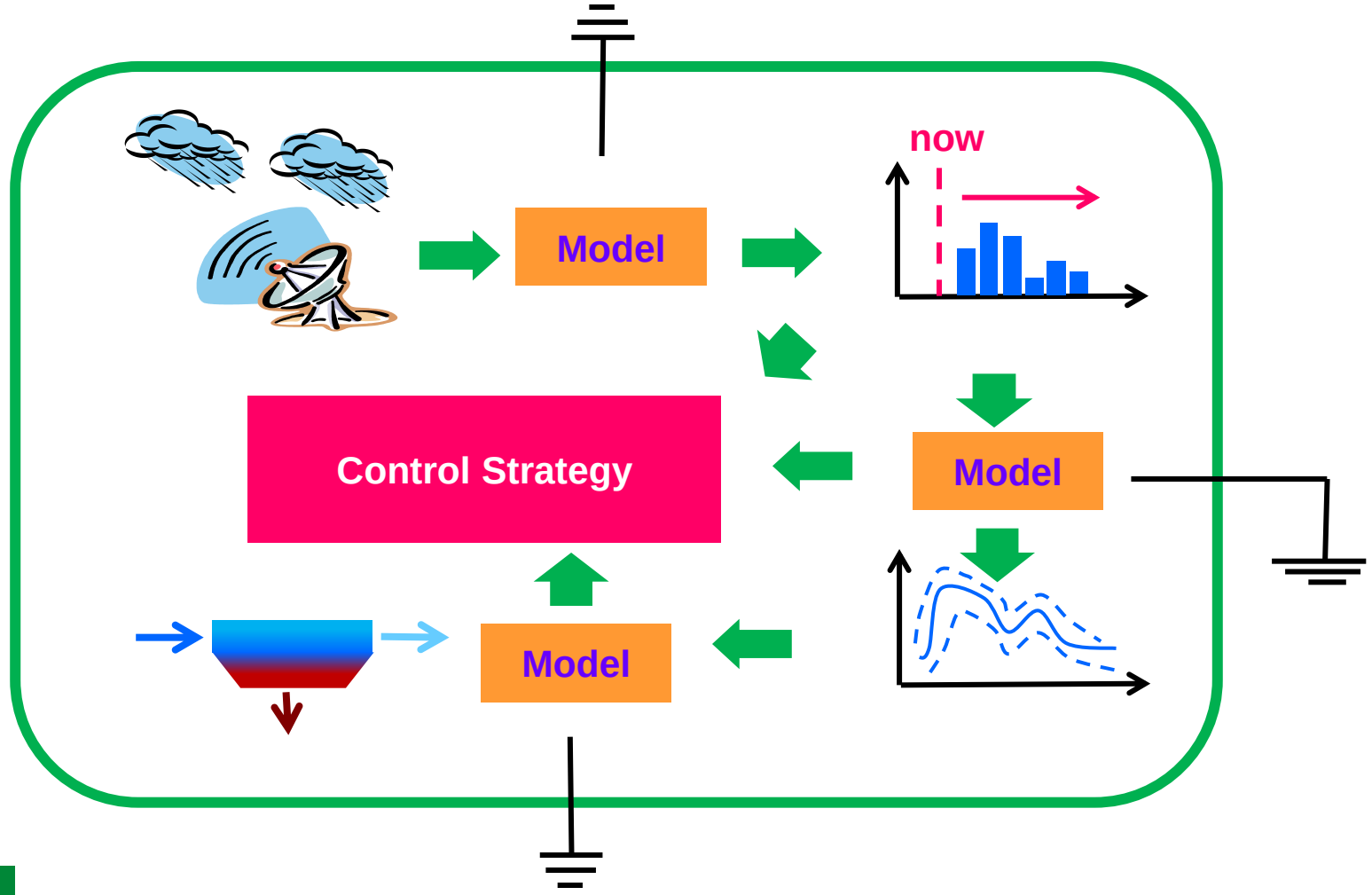
Measurements + Models + Forecasts + Uncertainty =

The happy operator

The fellowship of SWI – the long journey

Measurements + Models + Forecasts + Uncertainty =

The happy operator

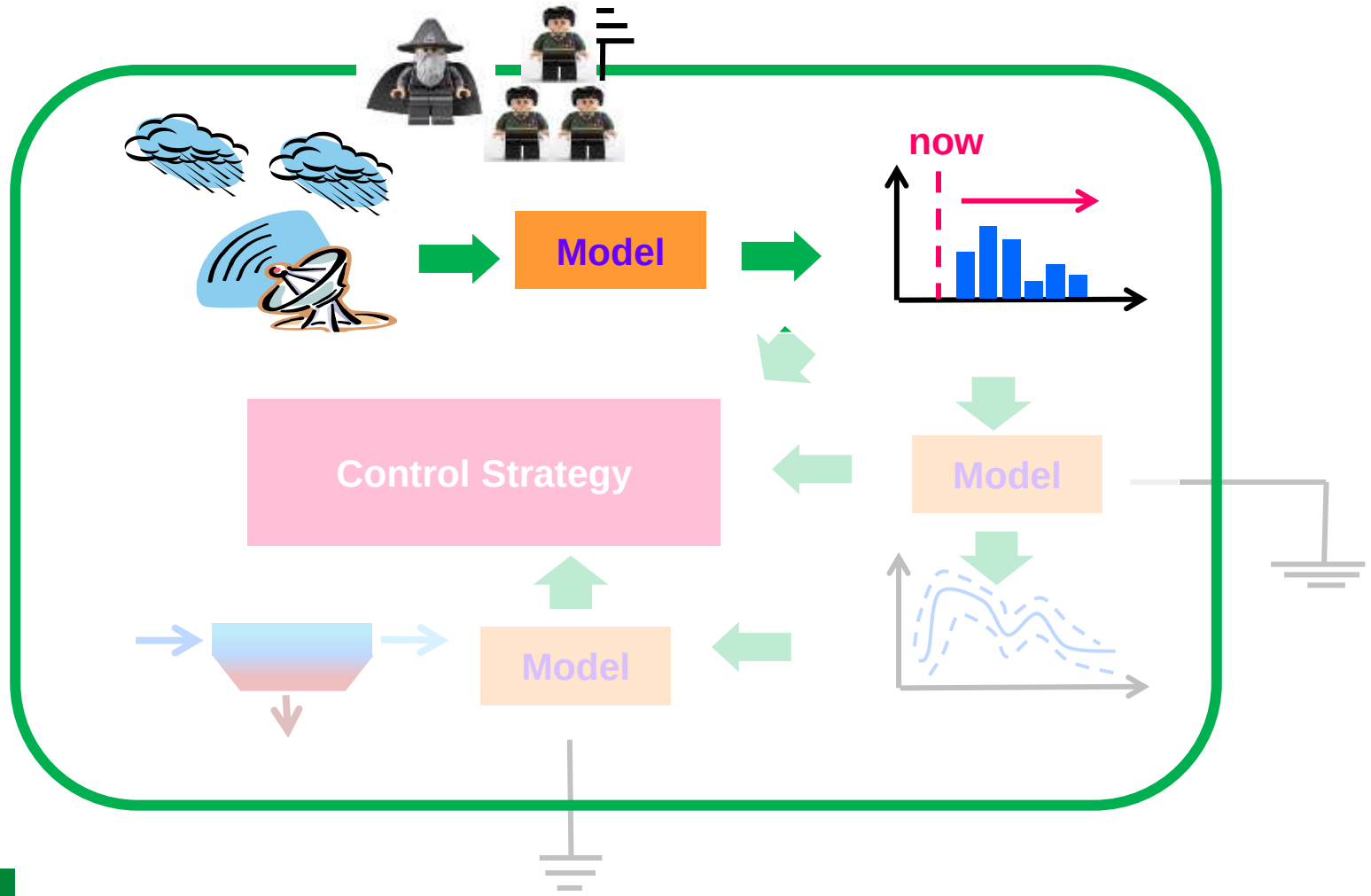


- Rainfall measurements
  is it going to rain?
- Short-term rainfall forecasts
  how much is it going to rain?
- Continuously updated hydrodynamic models
  how much water am I getting?
- Stochastic rainfall-runoff forecast
  how much can I trust those forecasts?
- WWTP forecast models
  can the plant take so much water?
- MPC strategy addressing uncertainty
  what should I do?

The fellowship of SWI – the long journey

Measurements + Models + Forecasts + Uncertainty =

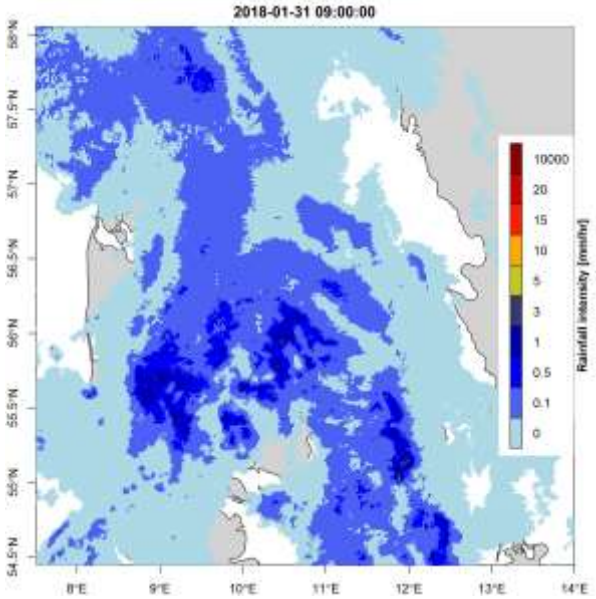
The happy operator

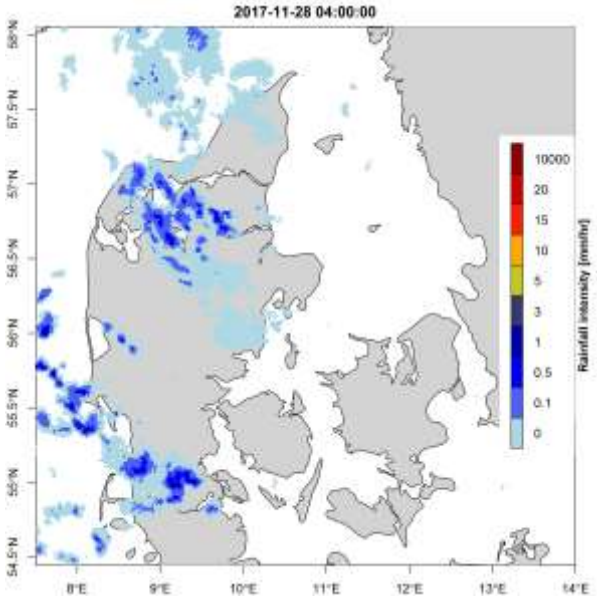


- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

Rainfall input

Where is it raining?
And how much?

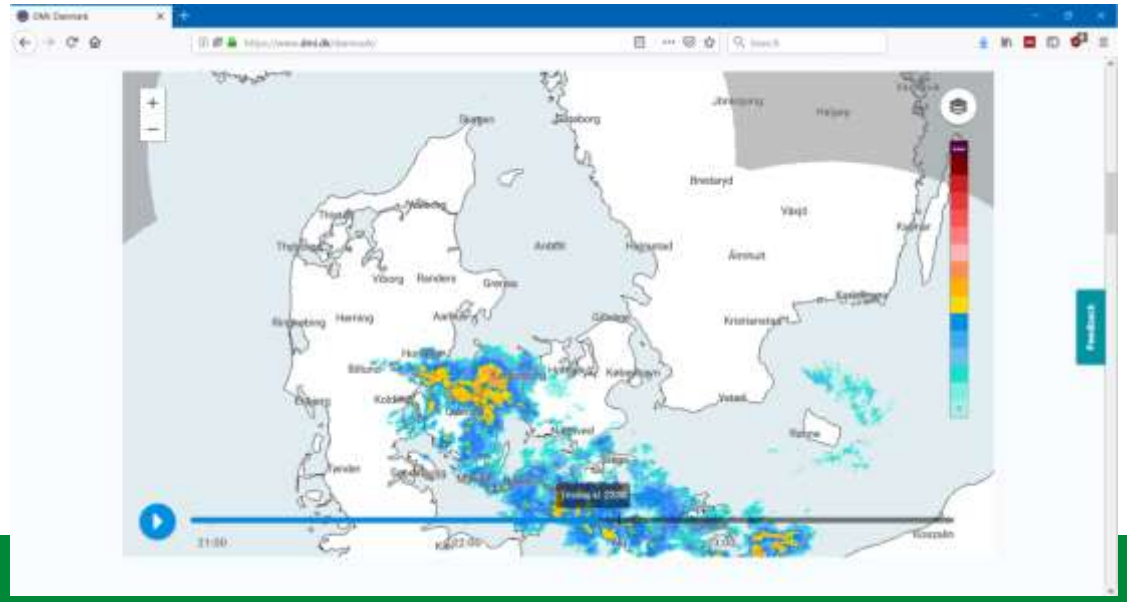




- Rainfall is not easy to measure

Rain gauge

Radar

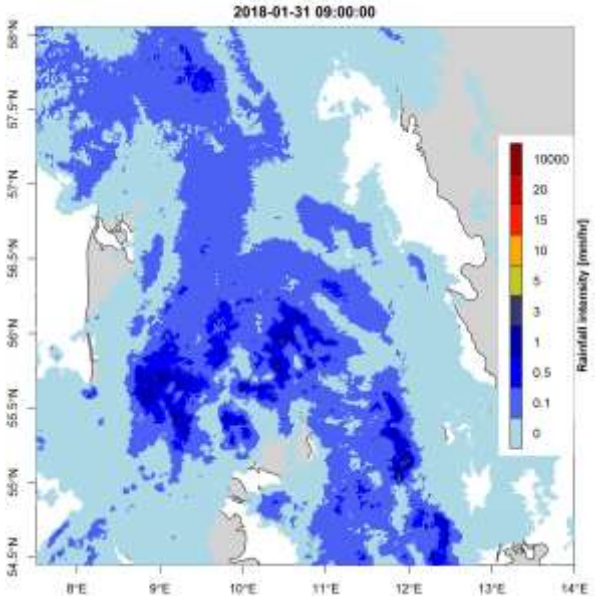


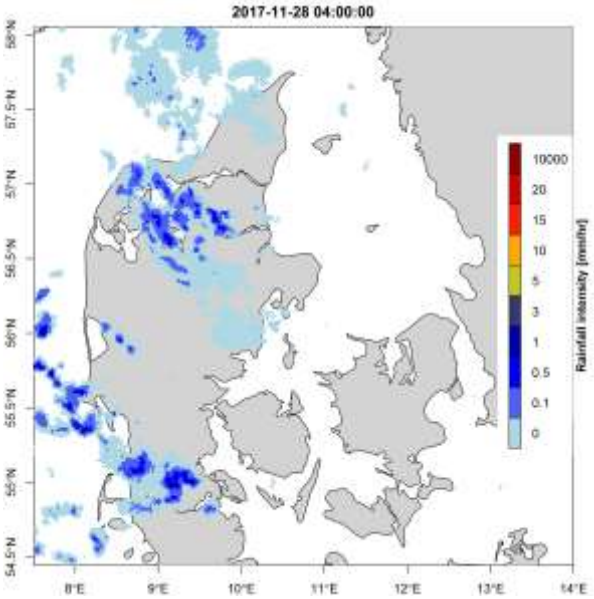
Lygten (5725)

Hellerup Kirkegård (5690)

Rainfall input

Where is it raining?
And how much?





- Rainfall is not easy to measure

	Volume	Spatial distribution
Rain gauges	√	X
Radar	X	√
Flow measurements	?	?

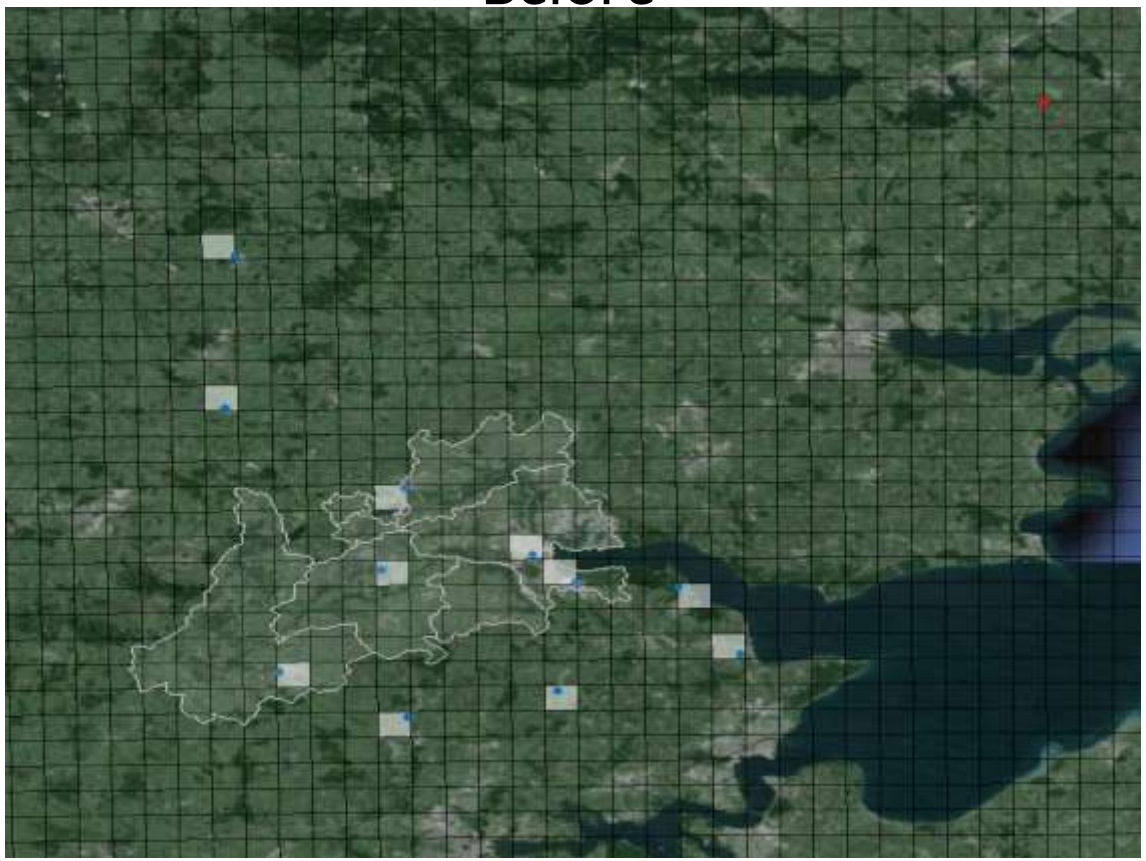
- But you can combine them!

Slide courtesy of Jonas Wield Pederesen

The new AAU Nowcaster

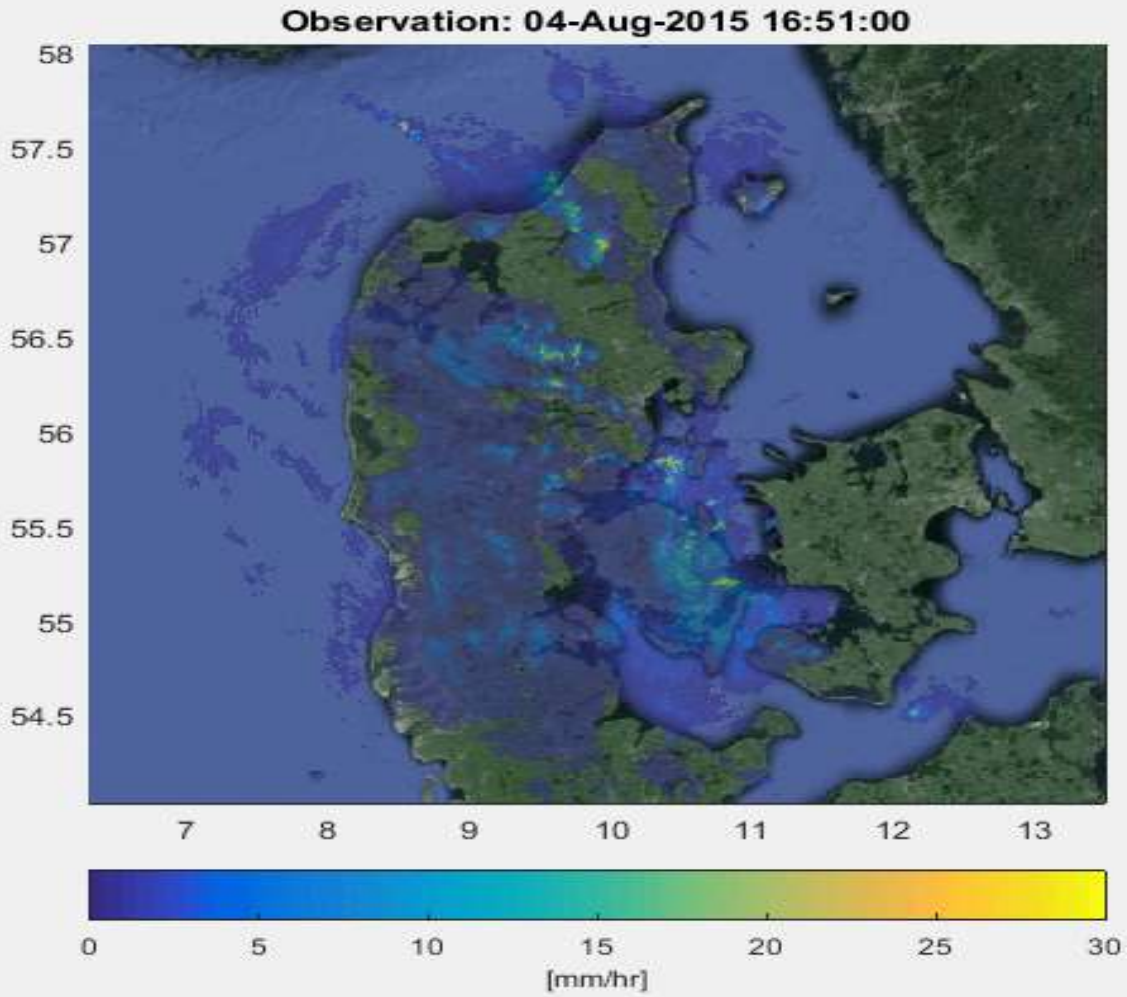
The spatial resolution is 16 times higher than before (500x500m vs 2000x2000m)

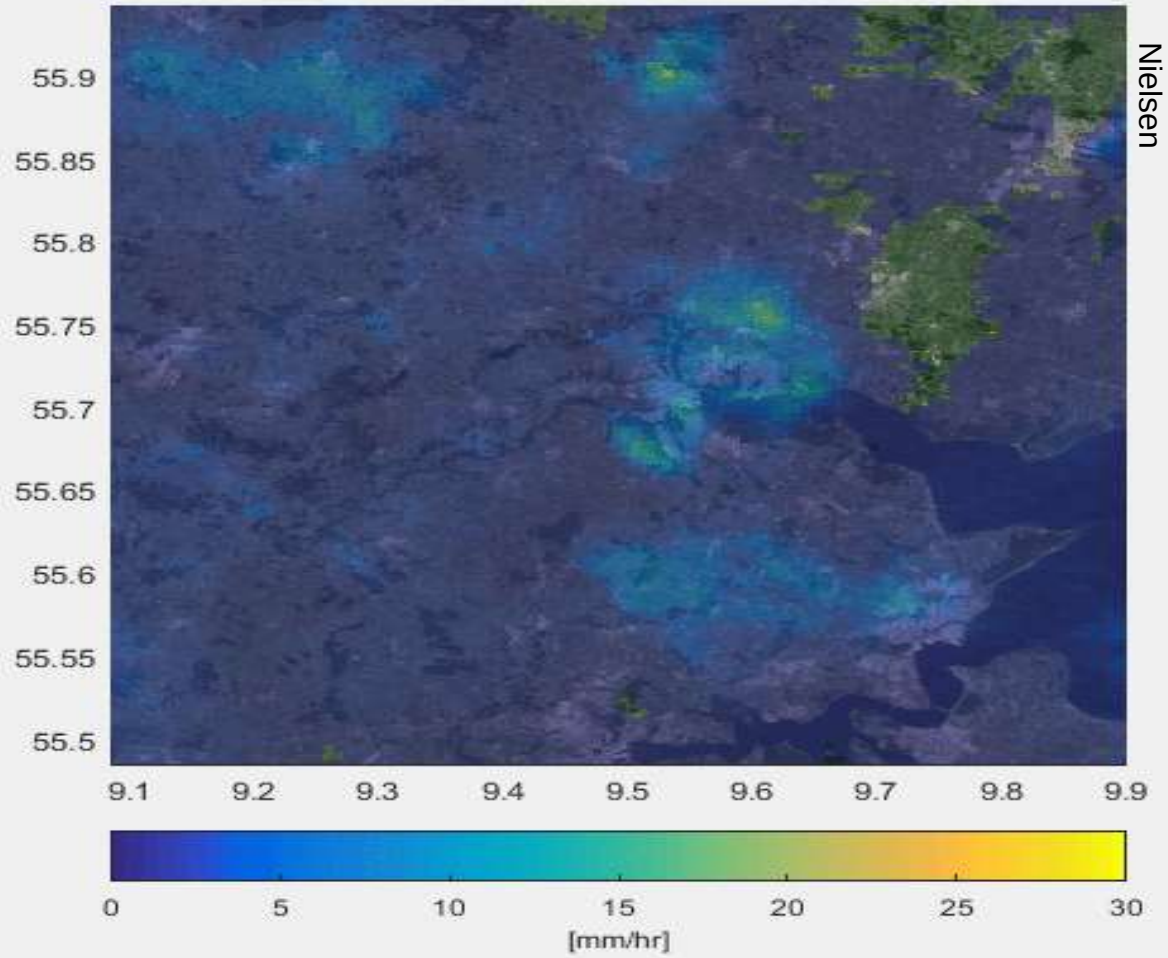
Before



After

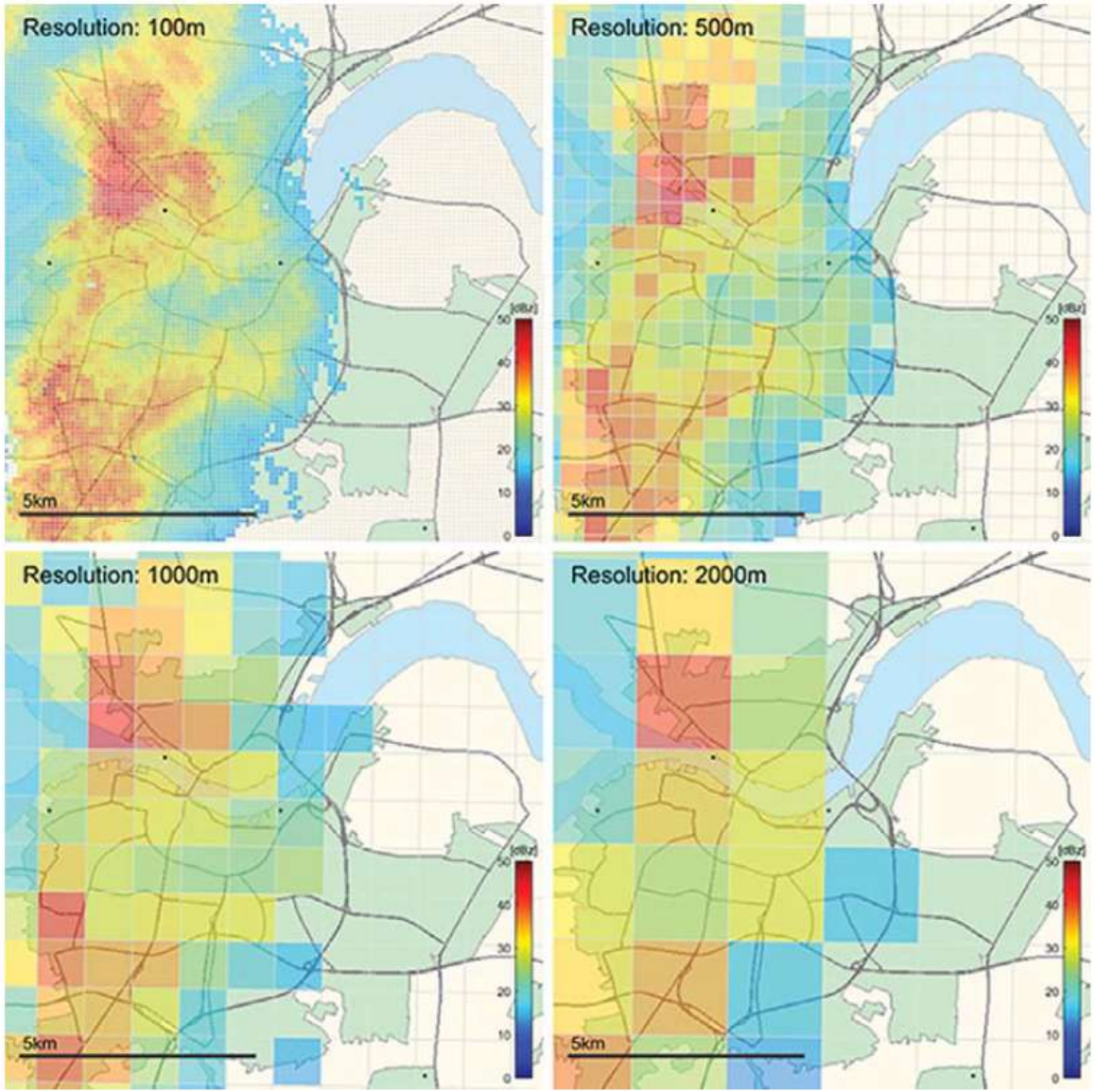
Demonstration af online nowcaster (WP-3)





Slide courtesy of Jesper Ellerbæk Nielsen

Radar resolution

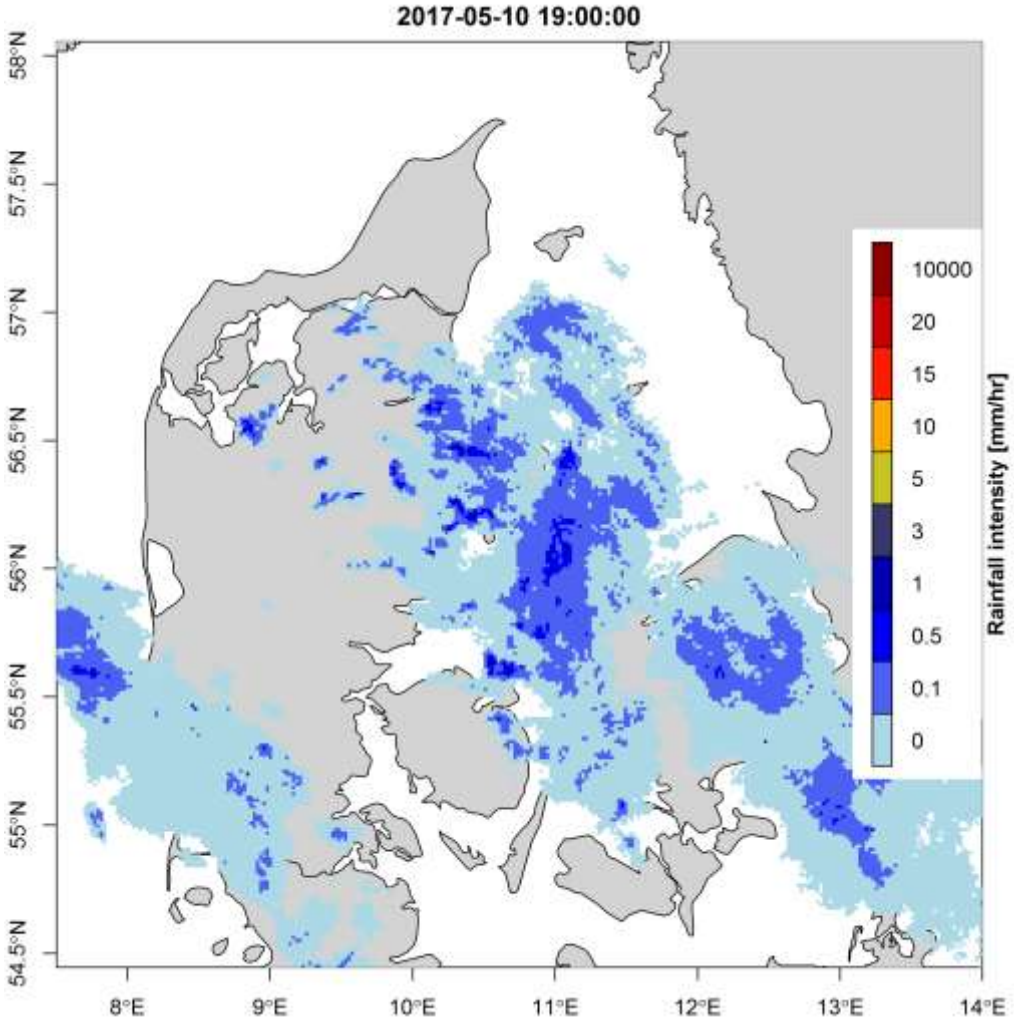


- Which one is the good one for the urban scale?
- Radar can are only useful to predict up to 2 hrs in the future
- What about longer horizons?

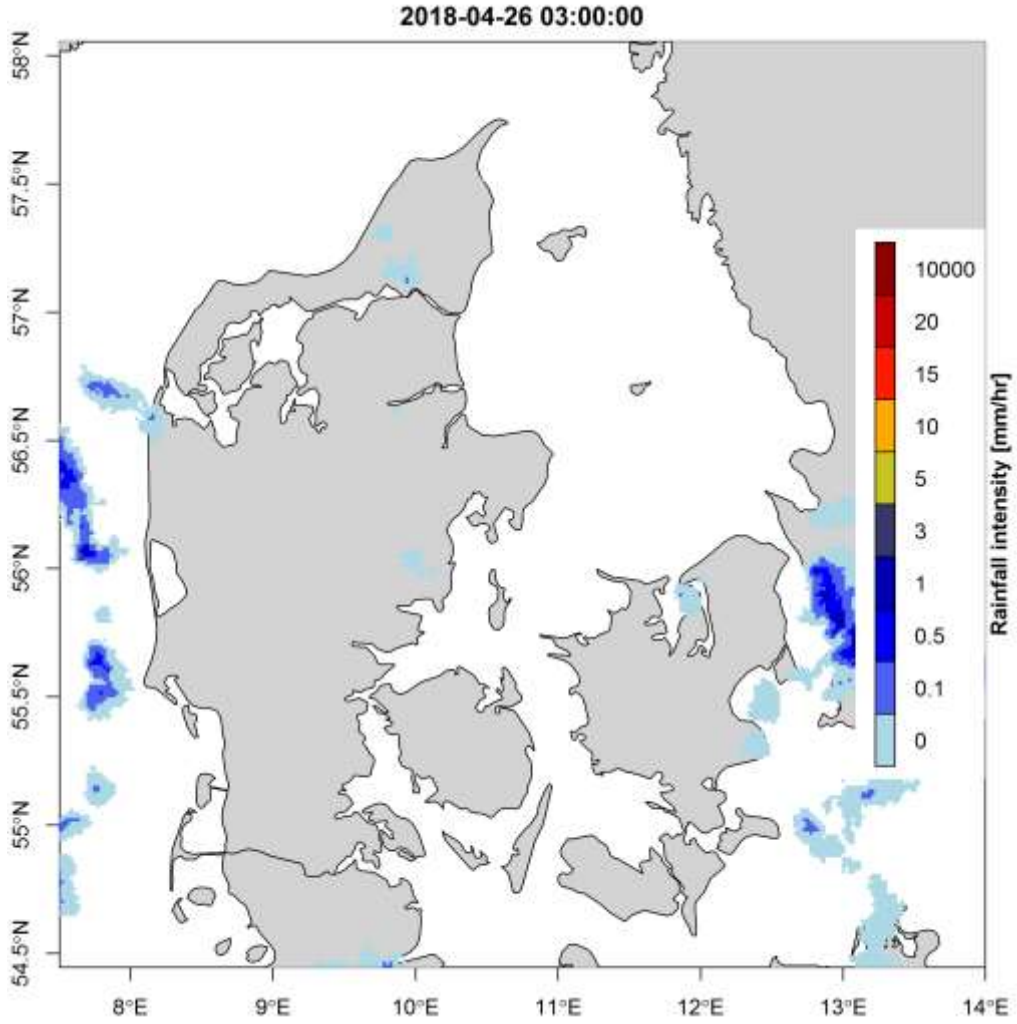
- Numerical Weather Prediction (NWP) models

Thorndahl, S., Einfalt, T., Willems, P., Nielsen, J. E., ten Veldhuis, M.-C., Arnbjerg-Nielsen, K., … Molnar, P. (2017). Weather radar rainfall data in urban hydrology. Hydrology and Earth System Sciences, 21(3), 1359–1380.

What the radar can see



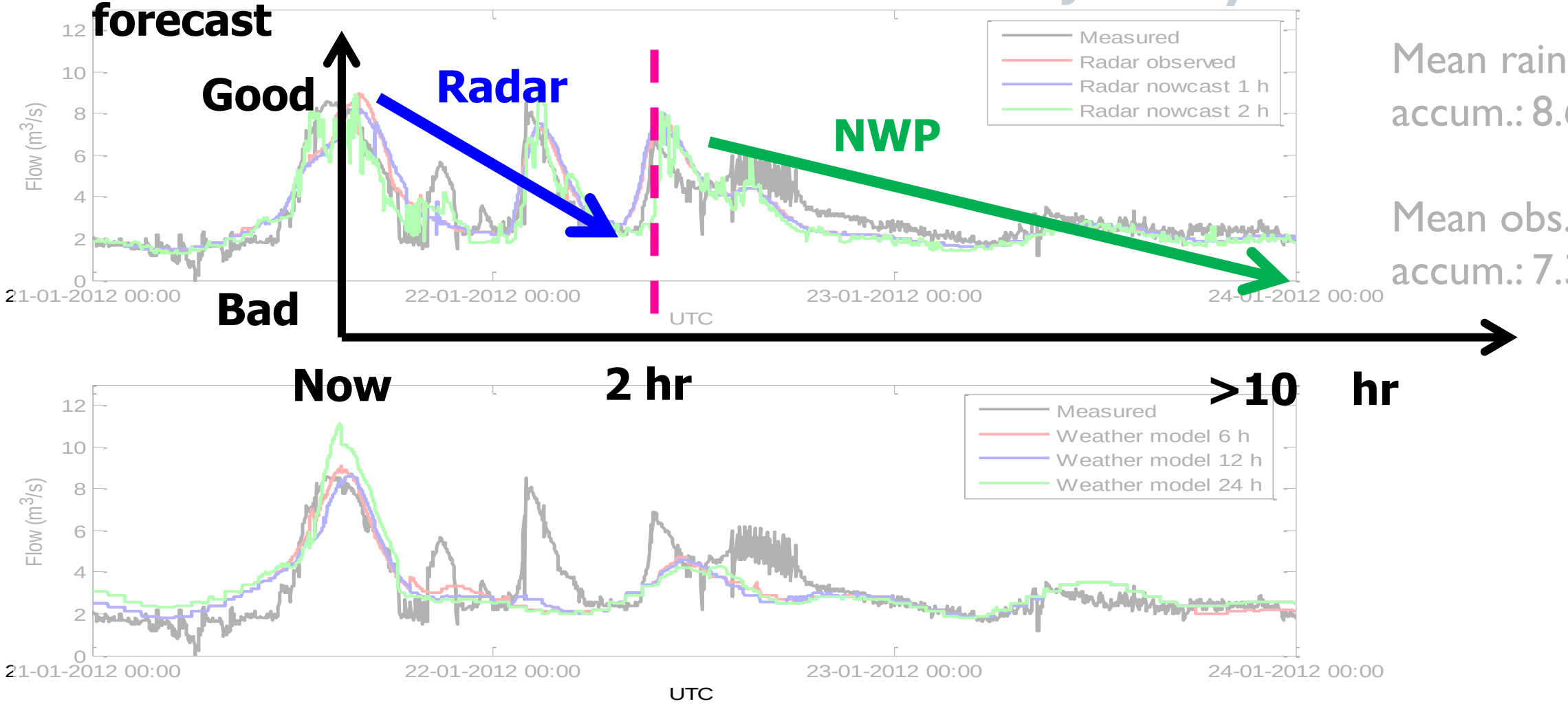
Radar is fine



not so good for the radar

Slide courtesy of Jonas Wield Pedersen

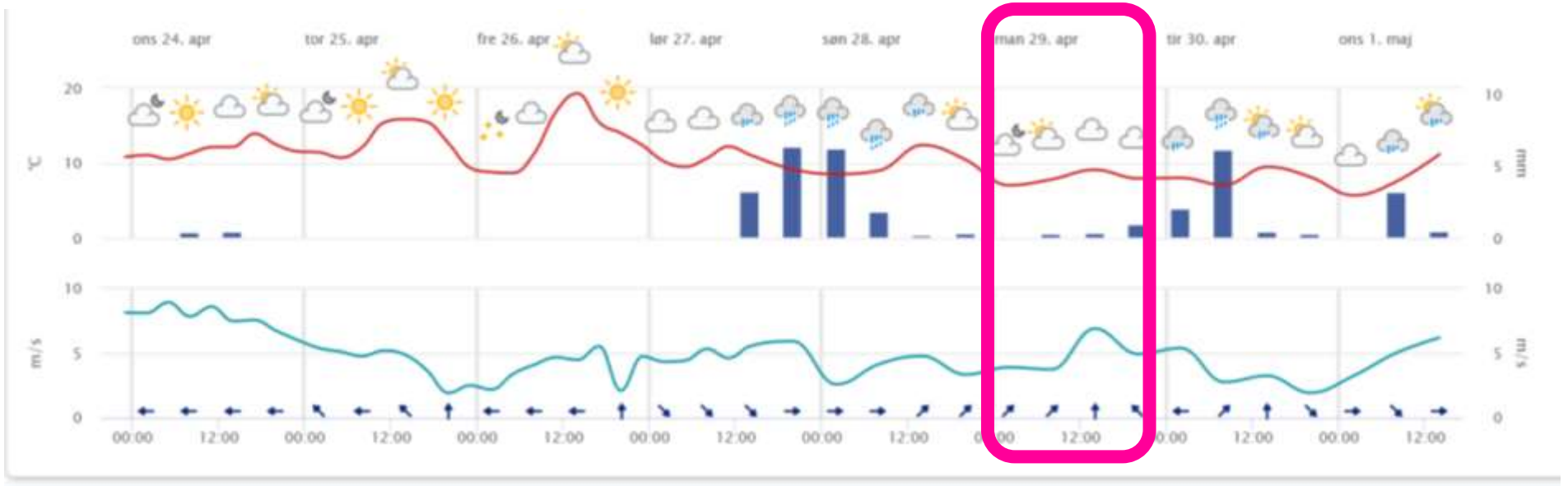
Flow forecast results - Event 6: 21 – 24 January 2012



Mean rain gauge accum.: 8.6 mm

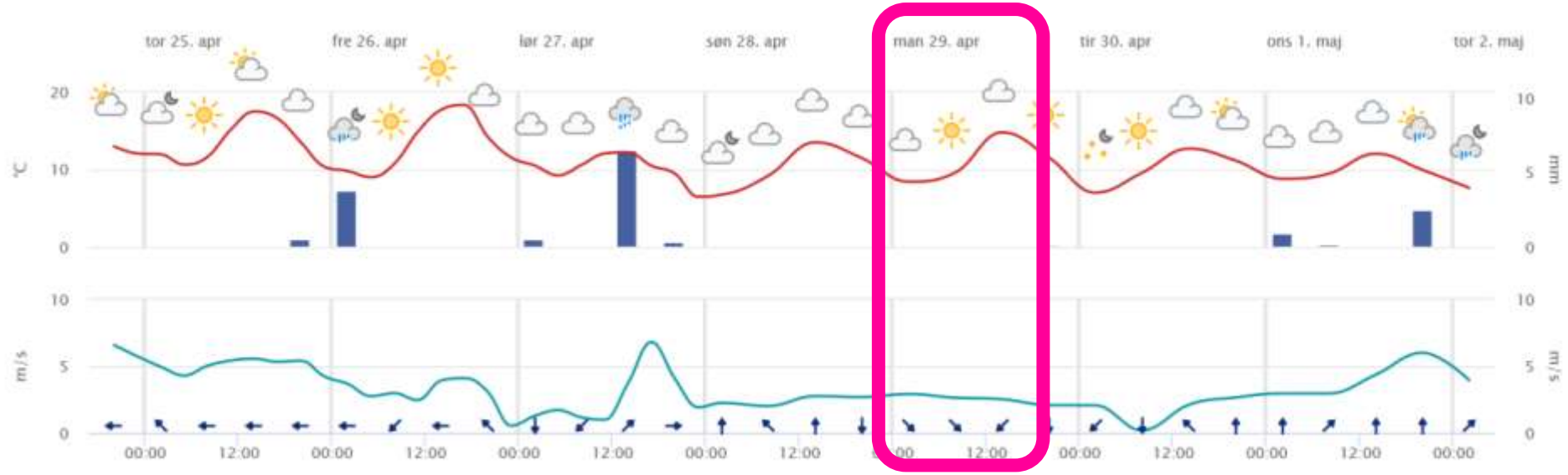
Mean obs. radar accum.: 7.3 mm

Hvordan er vejret i dag?



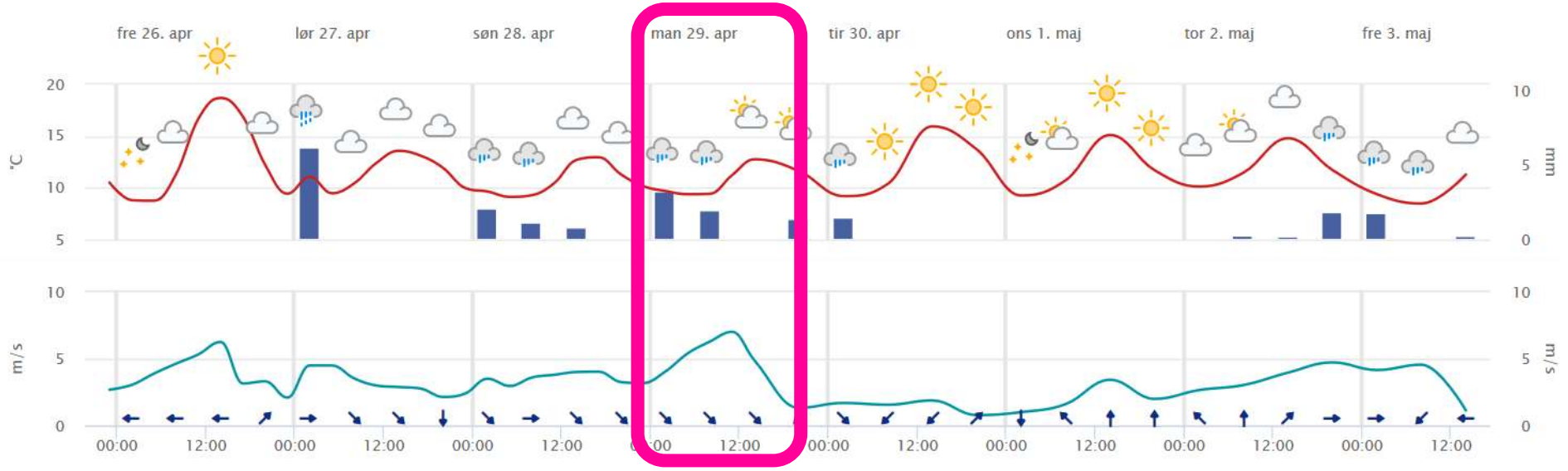
Tomorrow 22/04/2019	Tuesday 23/04/2019	Wednesday 24/04/2019	Thursday 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019
16°	16°	10°	14°	13°	13°	10°	12°	11°
Clear sky. Gentle breeze, 5 m/s from southeast. 0 mm precipitation.	Clear sky. Fresh breeze, 8 m/s from east-southeast. 0 mm precipitation.	Partly cloudy. Fresh breeze, 8 m/s from east. 0 mm precipitation.	Clear sky. Moderate breeze, 6 m/s from southeast. 0 mm precipitation.	Cloudy. Moderate breeze, 7 m/s from south-southwest. 0 mm precipitation.	Fair. Moderate breeze, 6 m/s from south-southwest. 0 mm precipitation.	Clear sky. Fresh breeze, 9 m/s from west-southwest. 0 mm precipitation	Rain showers. Moderate breeze, 7 m/s from south. 2.5 mm precipitation.	Partly cloudy. Moderate breeze, 7 m/s from west. 0 mm precipitation.

22/04



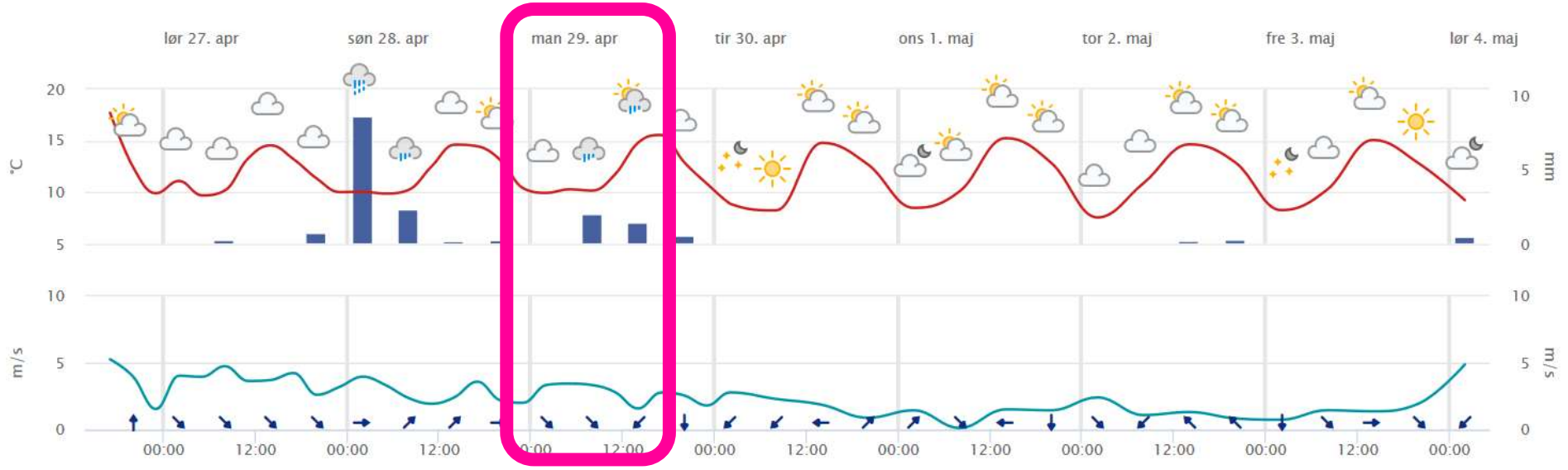
Tomorrow 23/04/2019	Wednesday 24/04/2019	Thursday 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019
16°	14°	16°	16°	12°	12°	13°	12°	11°
Clear sky. Fresh breeze, 8 m/s from east-southeast. 0 mm precipitation.	Clear sky. Moderate breeze, 7 m/s from east-southeast. 0 mm precipitation.	Partly cloudy. Moderate breeze, 6 m/s from east. 0 mm precipitation.	Partly cloudy. Gentle breeze, 4 m/s from east. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from southwest. 0 mm precipitation.	Cloudy. Gentle breeze, 4 m/s from south. 0 mm precipitation.	Clear sky. Gentle breeze, 4 m/s from north-northeast. 0 mm precipitation.	artly cloudy. ight breeze, m/s from outheast. 0 mm recipitation.	Rain showers. Gentle breeze, 5 m/s from south-southeast. 2.1 mm precipitation.

23/04



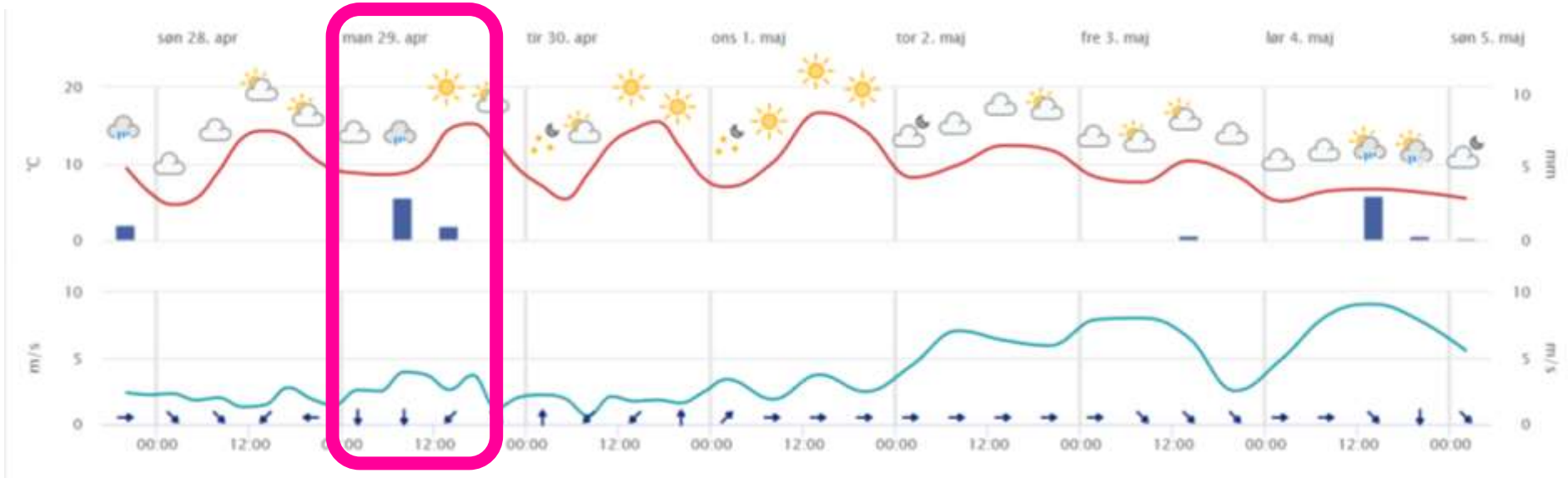
Tomorrow 24/04/2019	Thursday 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019	Thursday 02/05/2019
15°	18°	17°	13°	12°	12°	15°	13°	14°
Partly cloudy. Moderate breeze, 7 m/s from southeast. 0 mm precipitation.	Clear sky. Gentle breeze, 4 m/s from south-southeast. 0 mm precipitation.	Partly cloudy. Moderate breeze, 6 m/s from east. 0 mm precipitation.	Cloudy. Light breeze, 3 m/s from north-northwest. 0 mm precipitation.	Cloudy. Gentle breeze, 4 m/s from northwest. 0 mm precipitation.	Rain showers. Moderate breeze, 6 m/s from northwest. 1.8 mm precipitation.	Clear sky. Light breeze, m/s from orth-orthwest. 0 mm recipitation.	Clear sky. Light breeze, 3 m/s from south. 0 mm precipitation.	Rain. Gentle breeze, 4 m/s from south-southwest. 1.3 mm precipitation.

24/04



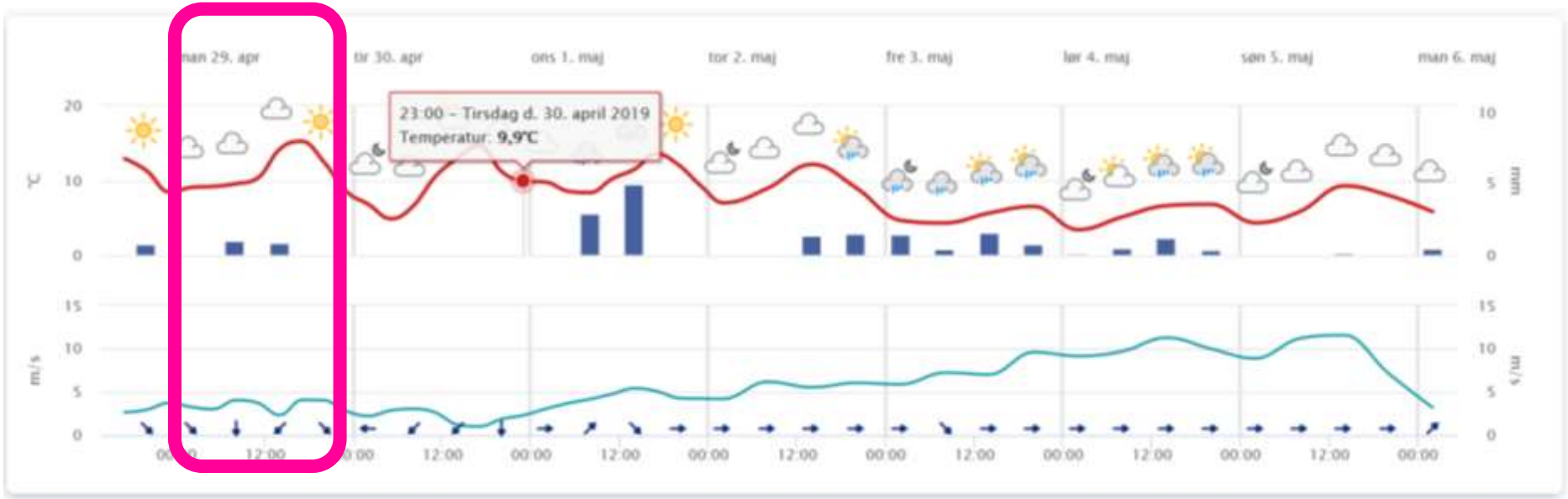
Tomorrow 25/04/2019	Friday 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	uesday /04/2019	Wednesday 01/05/2019	Thursday 02/05/2019	Friday 03/05/2019
18°	20°	14°	13°	14°	14°	14°	13°	14°
Fair. Light breeze, 3 m/s from south-southeast. 0 mm precipitation.	Partly cloudy. Gentle breeze, 4 m/s from east. 0 mm precipitation.	Rain. Gentle breeze, 5 m/s from north. 1.1 mm precipitation.	Fair. Light breeze, 3 m/ from south-southeast. 0 mm precipitation.	Cloudy. Light breeze, 2 m/s from northwest. 0 mm precipitation.	air. Light air, m/s from rth. 0 mm ecipitation.	Partly cloudy. Light breeze, 3 m/s from east. 0 mm precipitation.	Fair. Light breeze, 2 m/s from southeast. 0 mm precipitation.	Clear sky. Light breeze, 2 m/s from south-southeast. 0 mm precipitation.

25/04



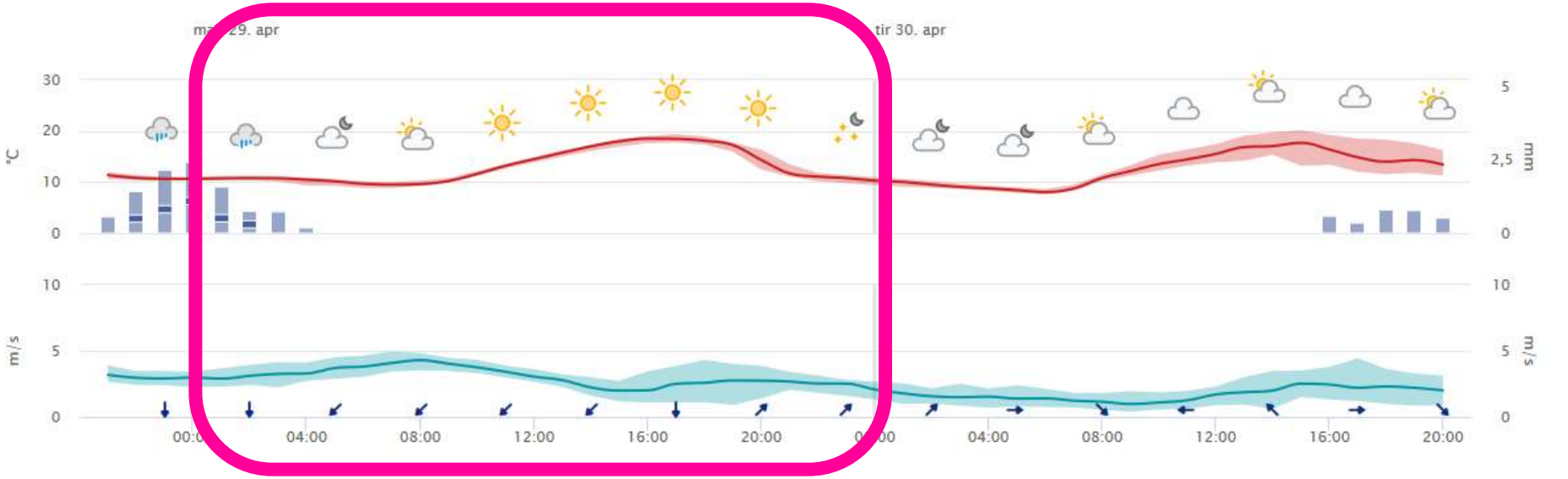
Tomorrow 26/04/2019	Saturday 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019	Thursday 02/05/2019	Friday 03/05/2019	Saturday 04/05/2019
19°	8°	13°	14°	13°	16°	12°	10°	7°
Partly cloudy. Light breeze, 3 m/s from east. 0 mm precipitation.	Heavy rain. Gentle breeze, 5 m/s from west-northwest. 5 mm precipitation.	Partly cloudy Light breeze, 3 m/s from east-northeast. 0 mm precipitation.	Fair. Light breeze, 2 m/s from north-northwest. 0 mm precipitation.	Clear sky. Light air, 1 m/s from northwest. 0 mm precipitation.	Clear sky. Light breeze, 3 m/s from southwest. 0 mm precipitation.	Partly cloudy. Moderate breeze, 7 m/s from west. 0 mm precipitation.	Cloudy. Moderate breeze, 7 m/s from northwest. 0 mm precipitation.	Partly cloudy. Fresh breeze, 10 m/s from west-northwest. 0 mm precipitation.

26/04



Tomorrow 27/04/2019	Sunday 28/04/2019	Monday 29/04/2019	Tuesday 30/04/2019	Wednesday 01/05/2019	Thursday 02/05/2019	Friday 03/05/2019	Saturday 04/05/2019	Sunday 05/05/2019
10°	14°	13°	12°	11°	12°	6°	7°	9°
Cloudy. Gentle breeze, 5 m/s from northwest. 0 mm precipitation.	Partly cloudy. Light breeze, 3 m/s from northeast. 0 mm precipitation.	Fair. Light air, 1 m/s from northwest. 0 mm precipitation.	Cloudy. Light breeze, 2 m/s from northwest. 0 mm precipitation.	Fair. Moderate breeze, 6 m/s from west-northwest. 0 mm precipitation.	Rain showers. Moderate breeze, 6 m/s from west-southwest. 1.3 mm precipitation.	Rain showers. Fresh breeze, 8 m/s from west-northwest. 1.4 mm precipitation.	Fair. Strong breeze, 13 m/s from west. 0 mm precipitation.	Partly cloudy. Strong breeze, 13 m/s from west-northwest. 0 mm precipitation.

28/04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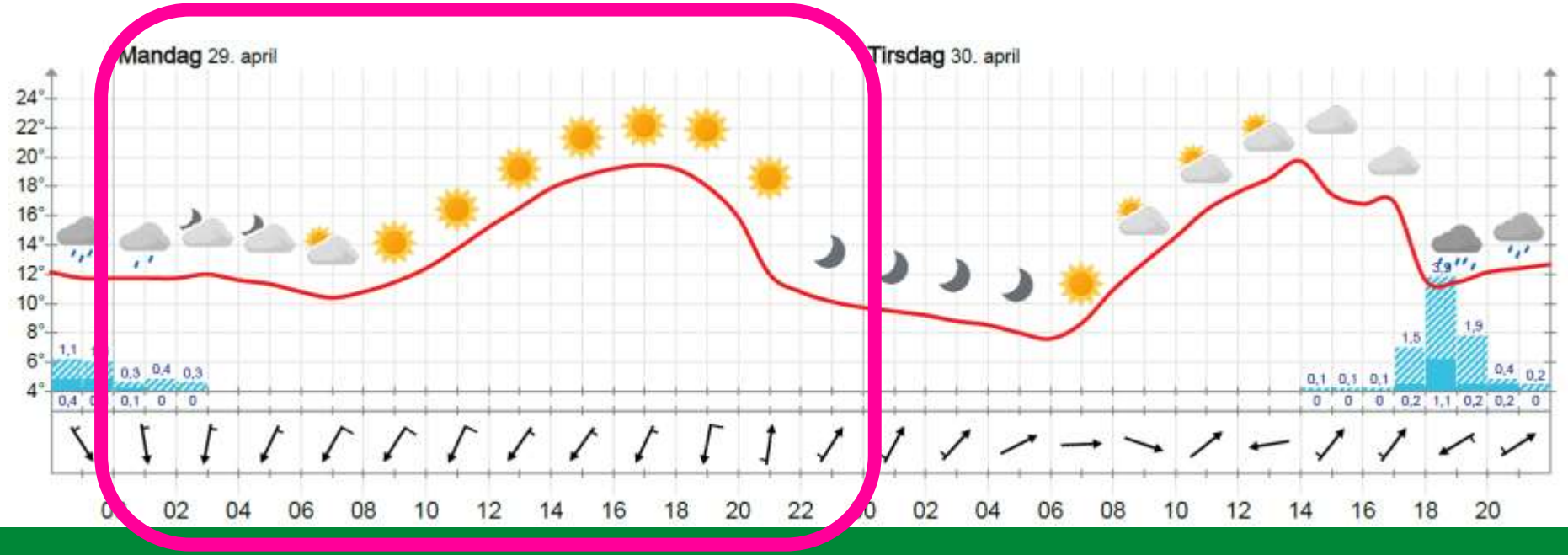
Mandag 29. april
Tirsdag 30. april
02
04
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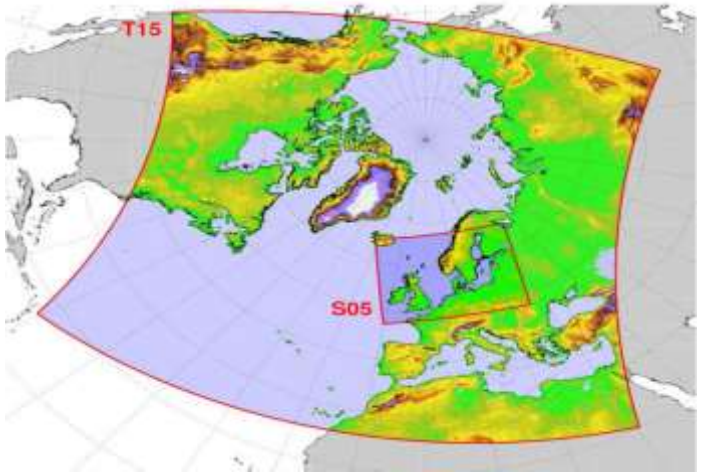
22

How weather forecasts are made?

The DMI-HIRLAM-S05 model



- Horizontal resolution = 0.05° (5.5 km)
- Time Step = 1h
- Forecast length = 54h
- Forecast frequency = 4 times per day
- Members = 25

5 ≠ model structures

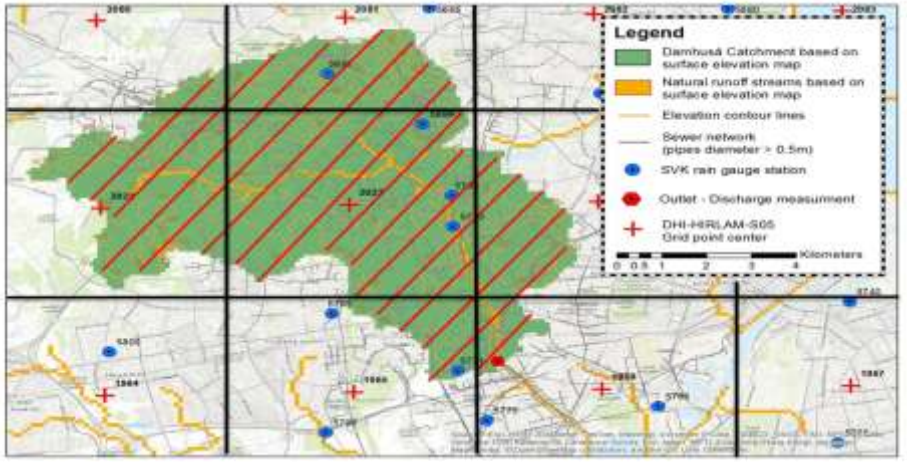
5 ≠ initial conditions

Ensemble members	STRACO		KF/RK		STRACO
		Stoc. Phys.		Stoc. Phys.	Pert. Roughn.
Ini. cond. 1	1	6	11	16	21
Ini. cond. 2	2	7	12	17	22
Ini. cond. 3	3	8	13	18	23
Ini. cond. 4	4	9	14	19	24
Ini. cond. 5	5	10	15	20	25

Slide courtesy of Dr. Vianney Courdant

Context vs. Model Uncertainty

what do we ask to the model?



Meteorological perspective

↓

Weather behavior, pattern, feature

↓

The big picture

Urban hydrology perspective

↓

Local value with high resolution

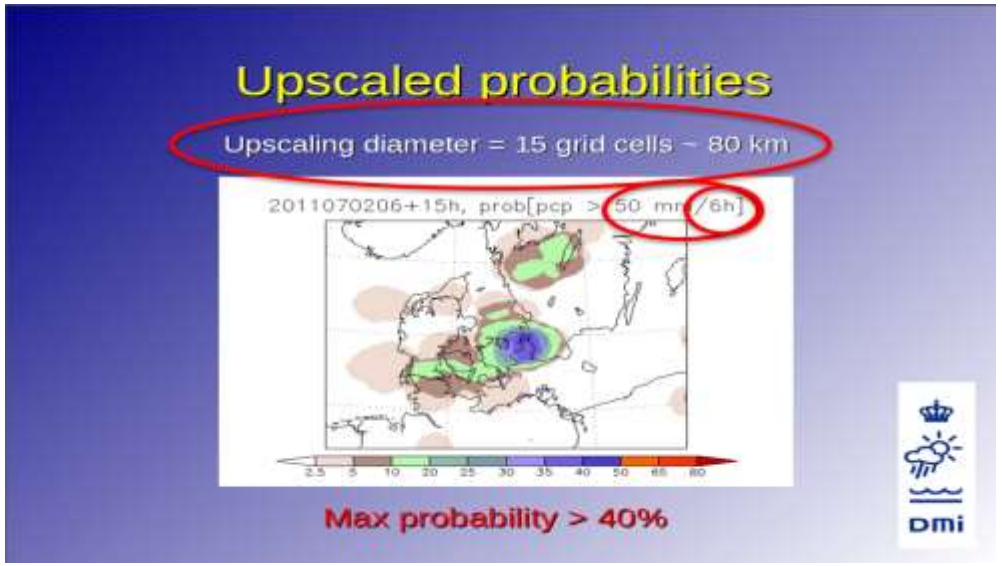
↓

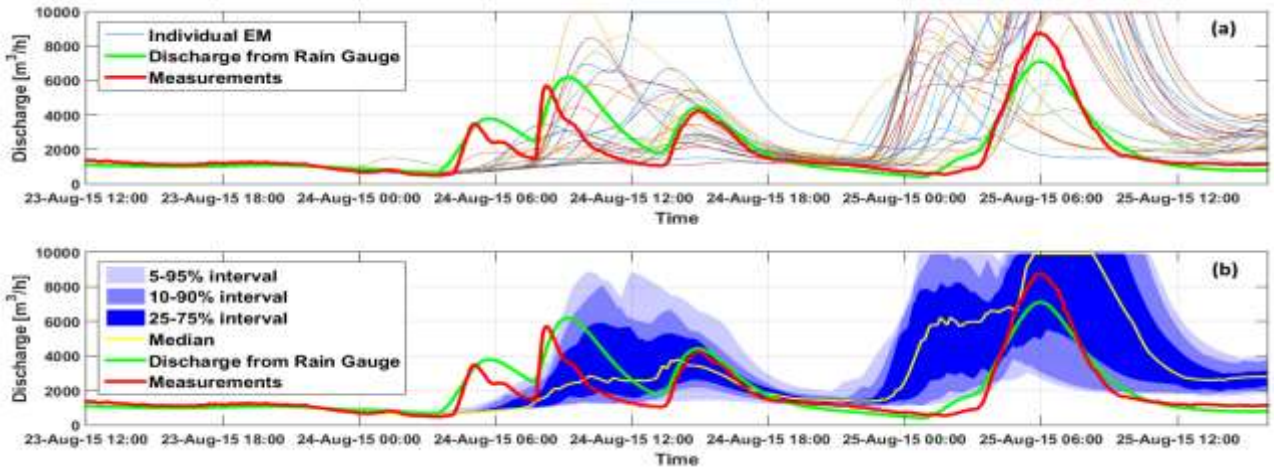
The pixel

Slide courtesy of Dr. Vianney Courdant

Context vs. Model Uncertainty

what do we ask to the model?





Meteorological perspective

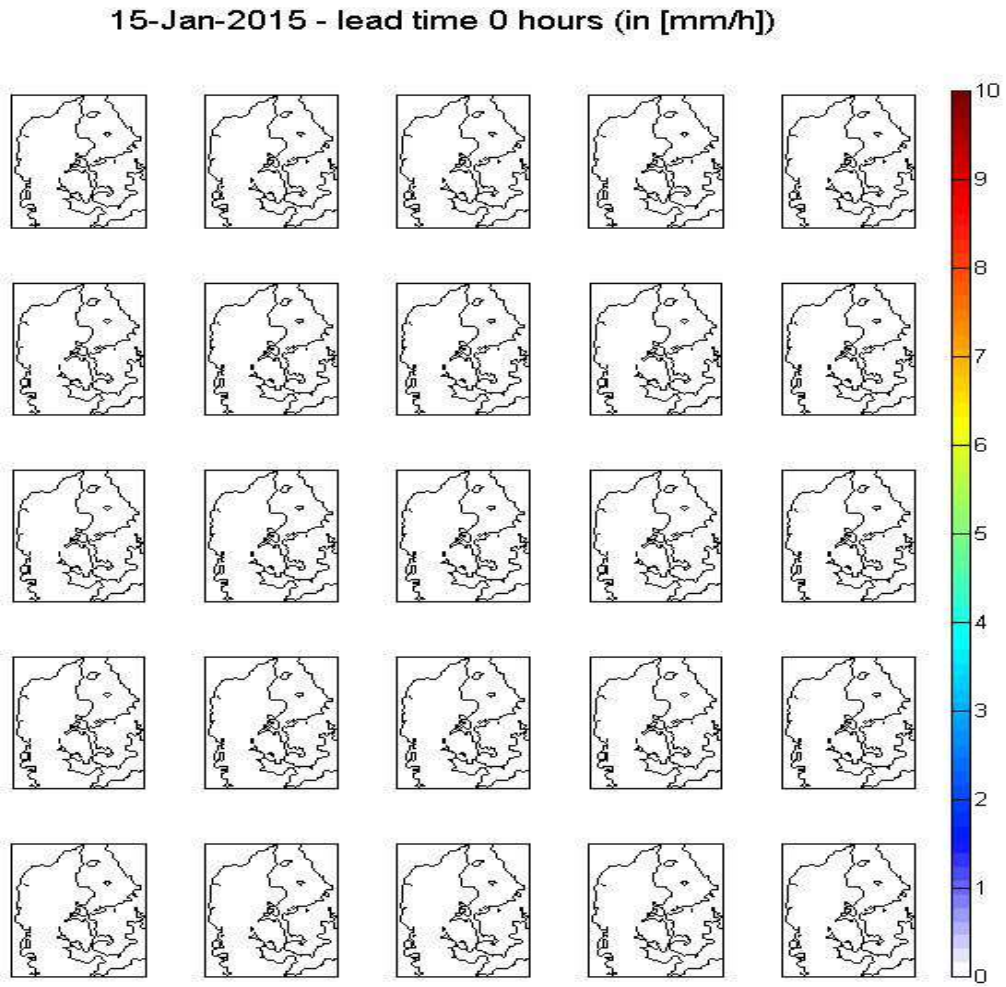
These weather forecast are great!

Urban hydrology perspective

These weather forecast are crap

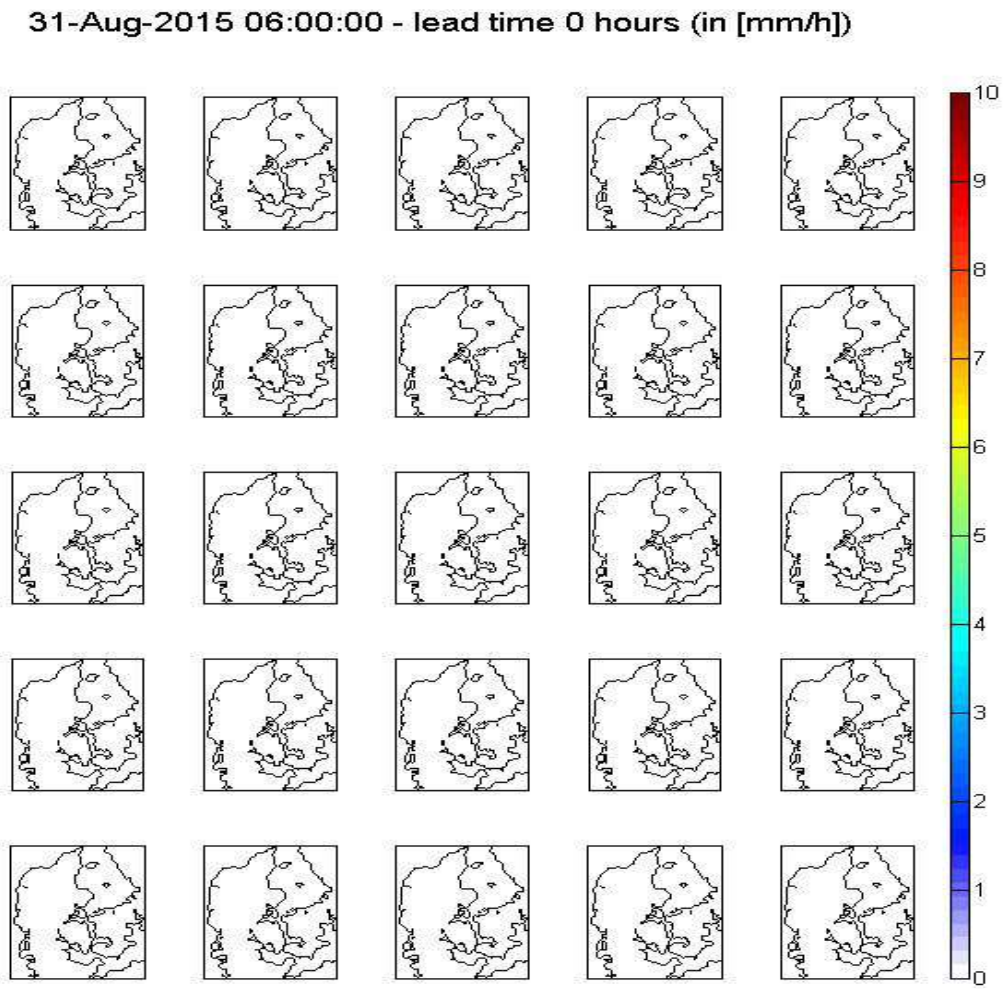
Slide courtesy of Dr. Vianney Courdant

DMI model prediction (winter)



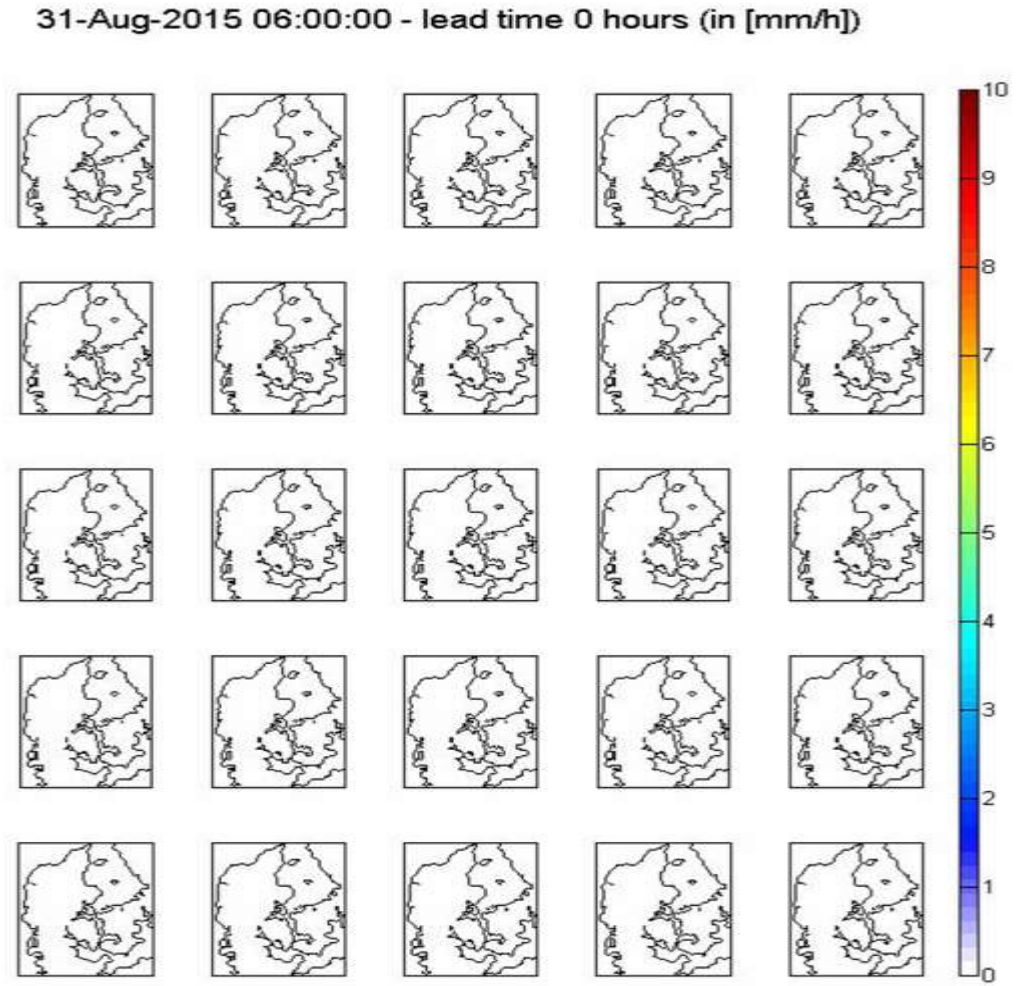
Slide courtesy of Dr. Vianney Courdant

DMI model prediction (summer)



Slide courtesy of Dr. Vianney Courdant

DMI model prediction (summer)



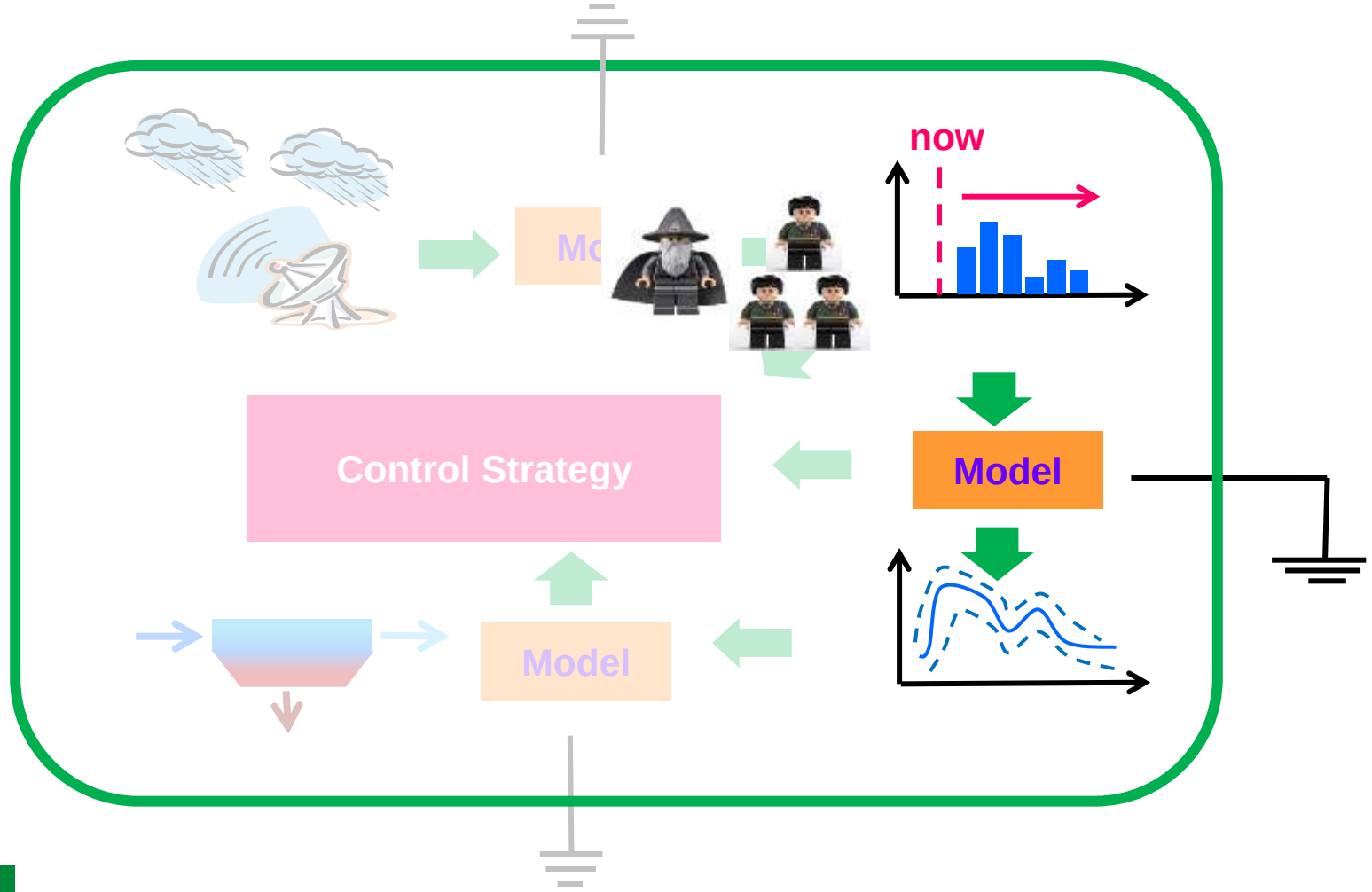
25 (physically based) models = 25 different results

Slide courtesy of Dr. Vianney Courdant

The fellowship of SWI – the long journey

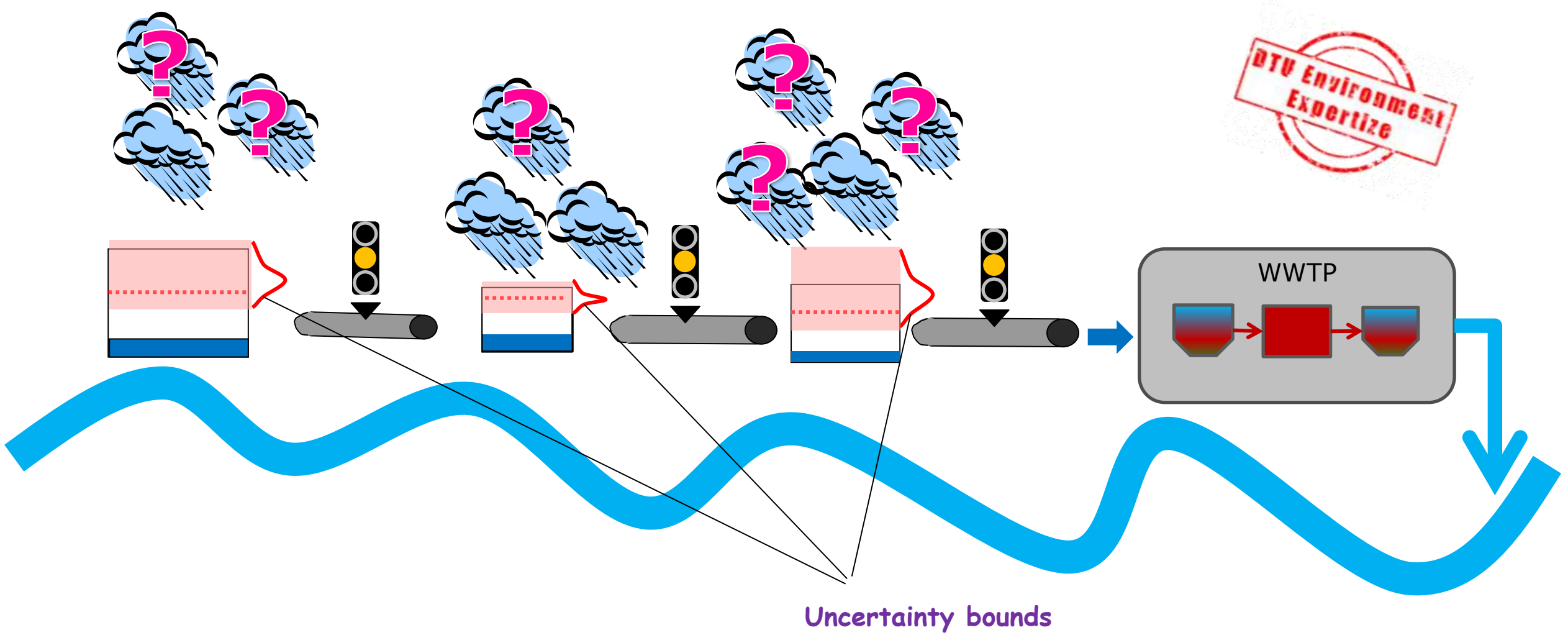
Measurements + **Models** + **Forecasts** + **Uncertainty** =

The happy operator

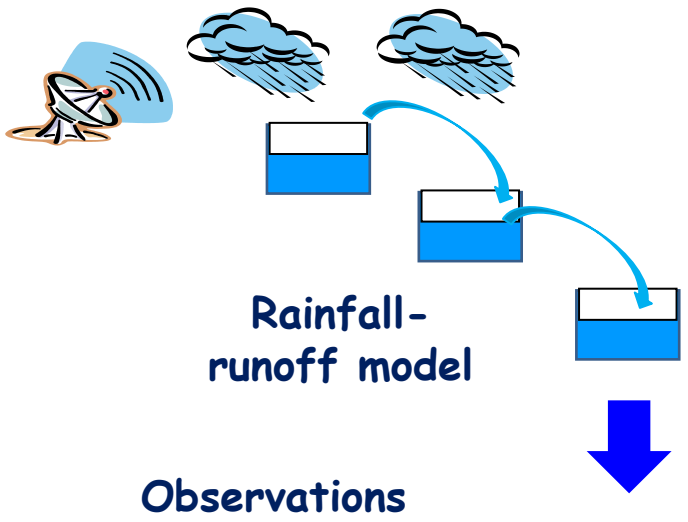


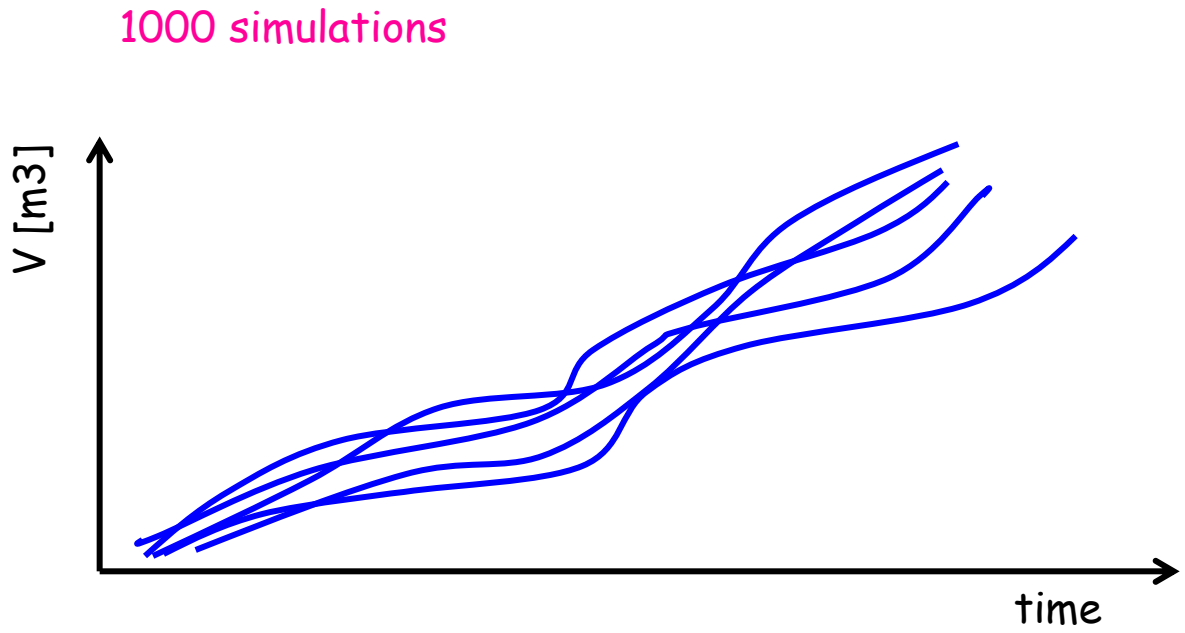
- Rainfall measurements
- Short-term rainfall forecasts
- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
- WWTP forecast models
- MPC strategy addressing uncertainty

Model Predictive Control with uncertainty



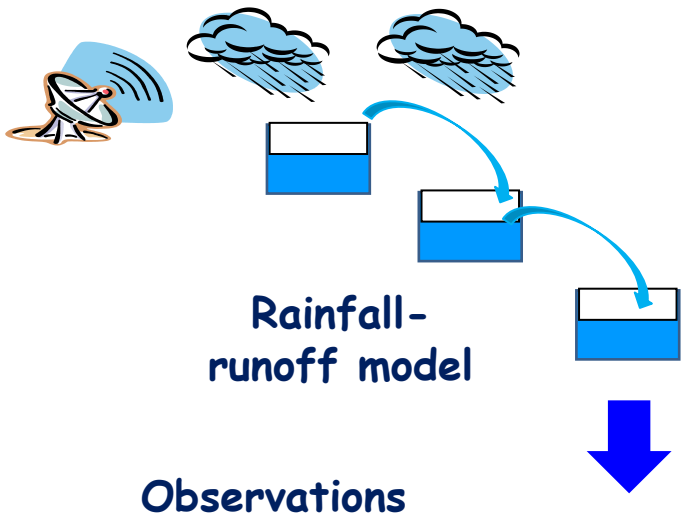
Stochastic runoff forecasts

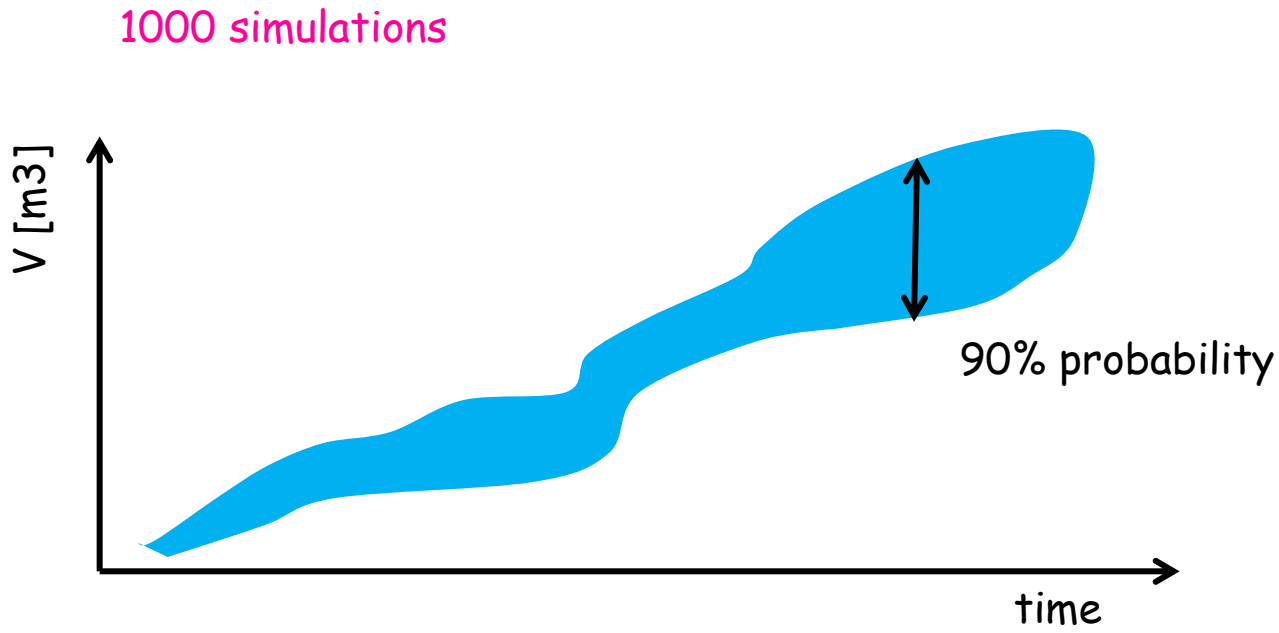




Löwe et al. (2014). J. Hydrology, 512, doi:10.1016/j.jhydrol.2014.03.027 .

Stochastic runoff forecasts



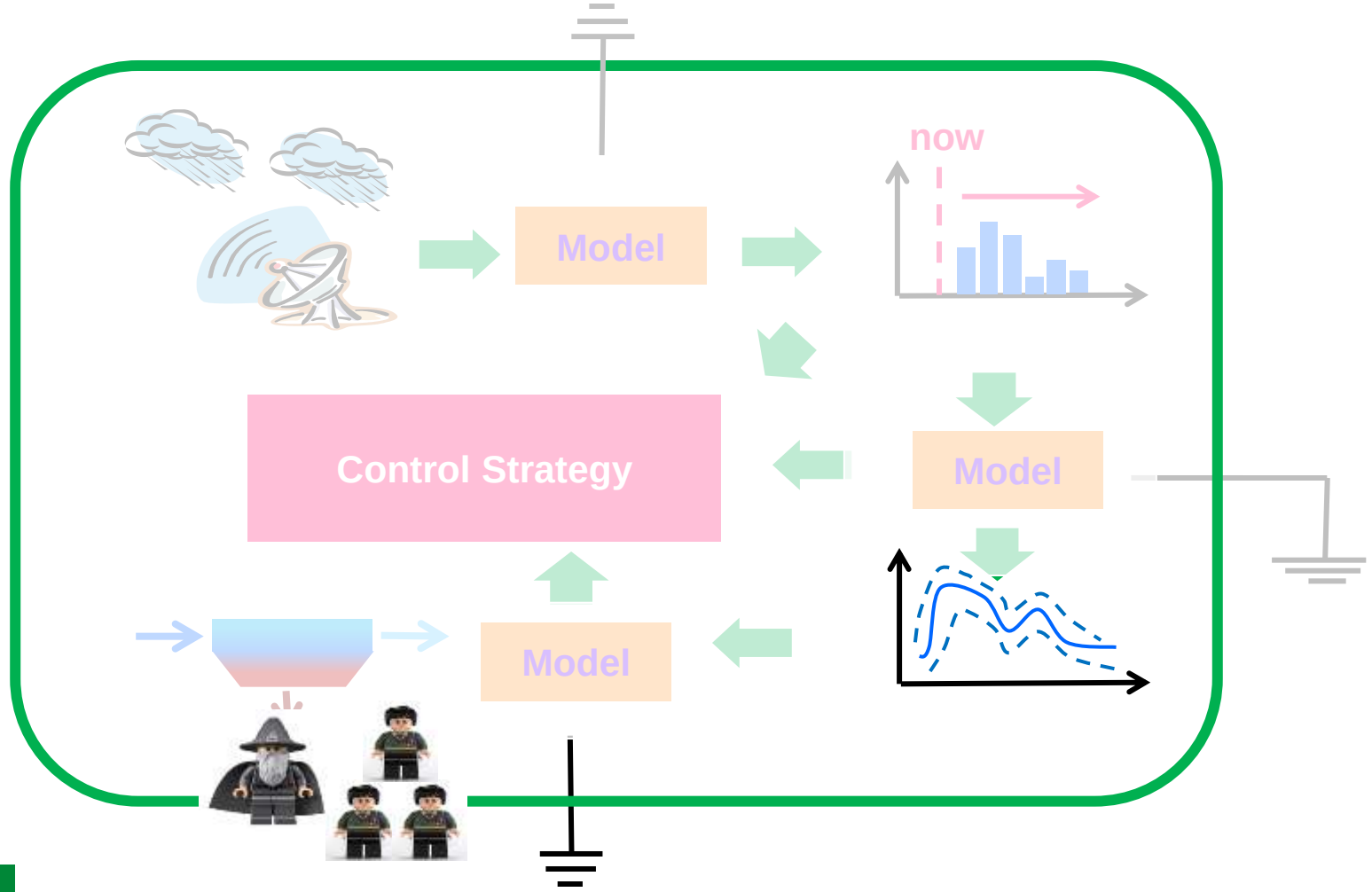


Löwe et al. (2014). J. Hydrology, 512, doi:10.1016/j.jhydrol.2014.03.027 .

The fellowship of SWI – the long journey

Measurements + Models + Forecasts + Uncertainty =

The happy operator



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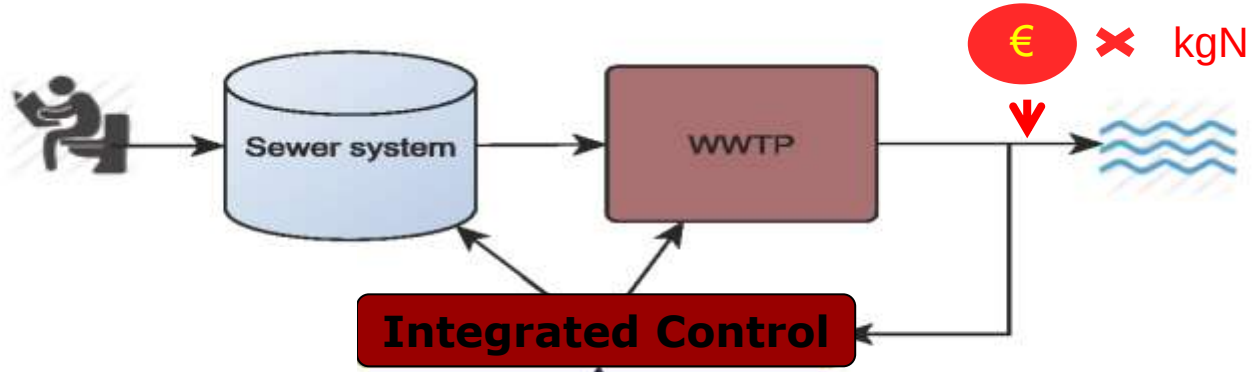
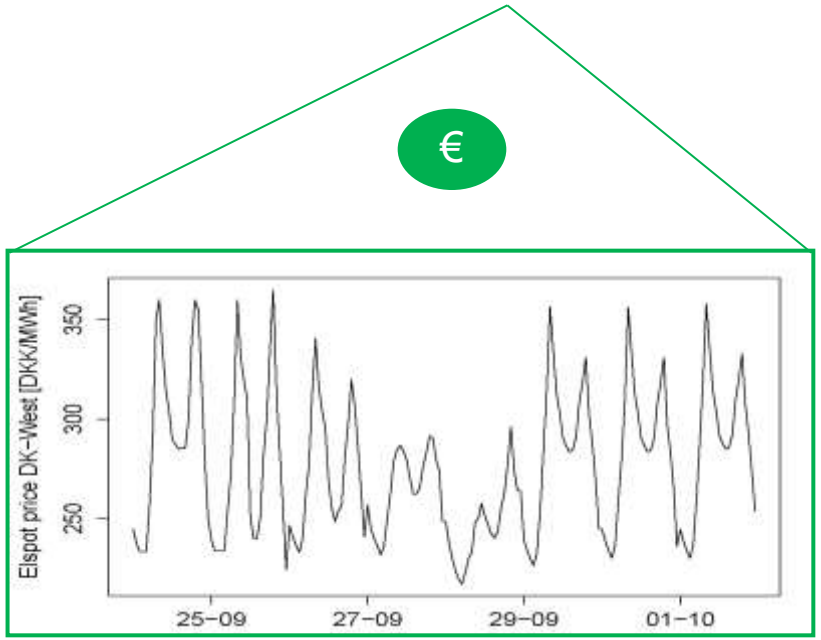
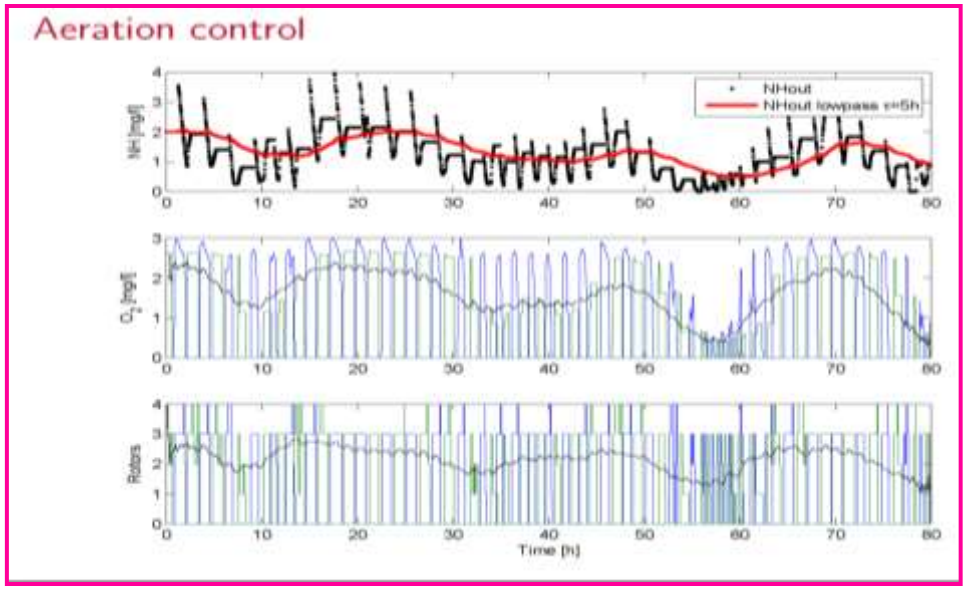
Controlling the WWTP based on energy prices

the Blue Kolding example

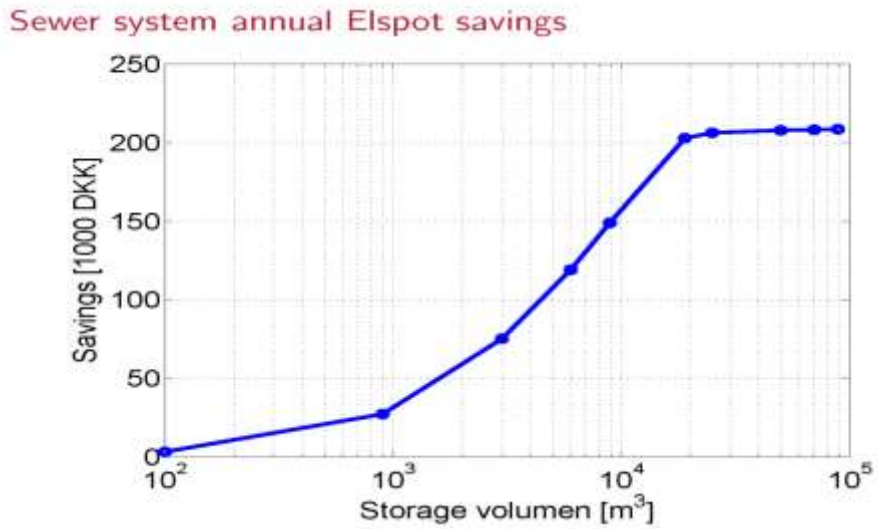


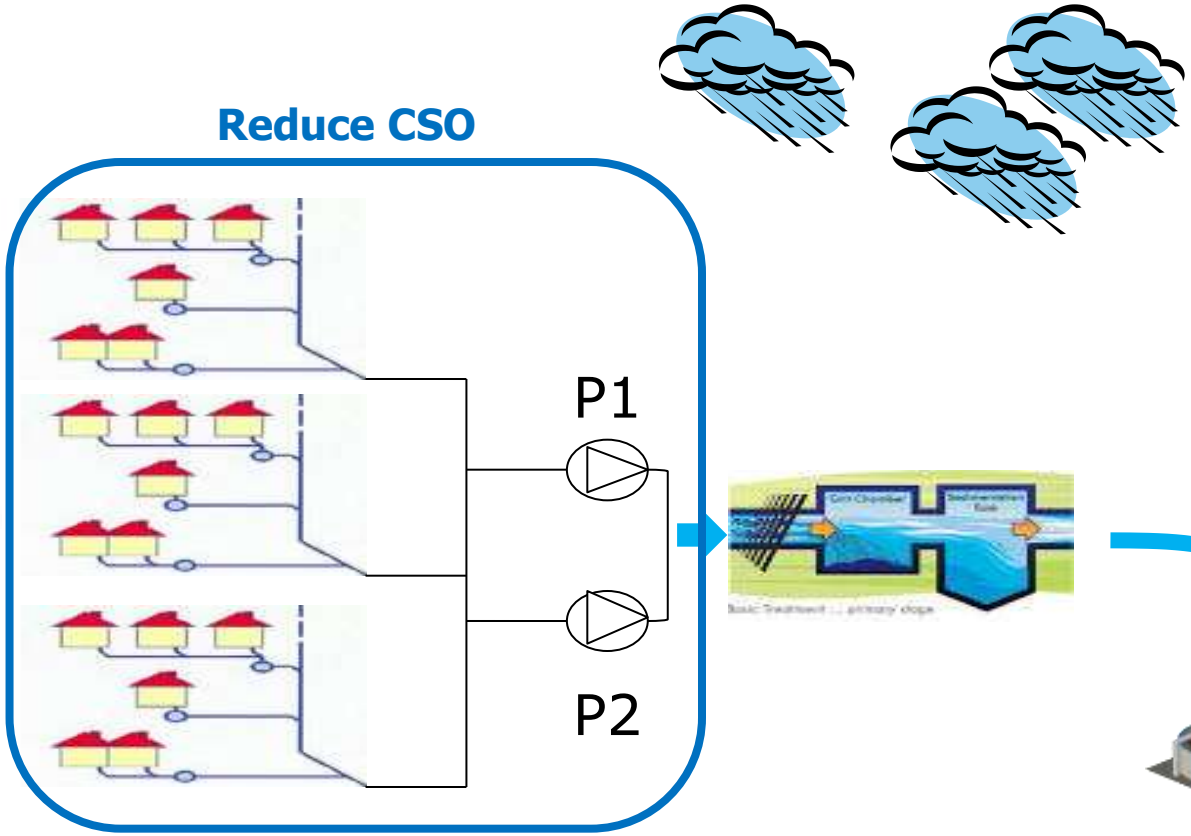




Slide courtesy of Rasmus Fogtmann Halvgaard

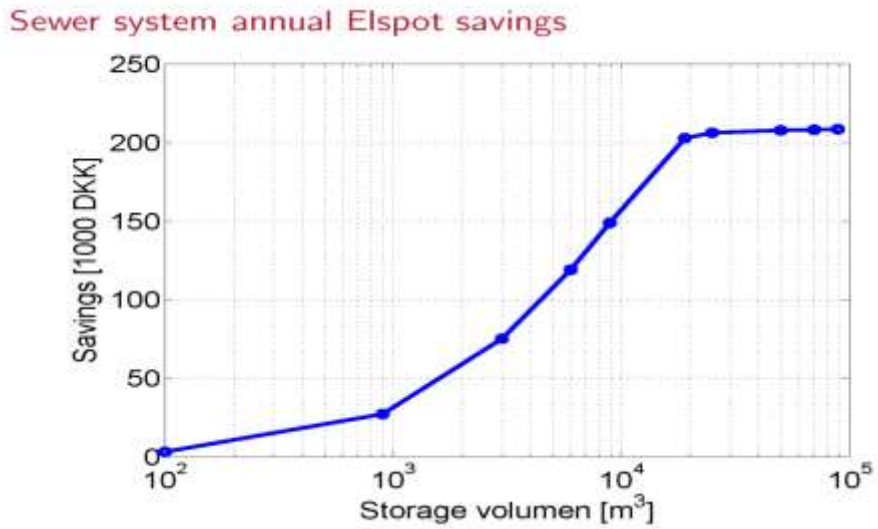
Controlling the WWTP based on energy prices – moving upstream

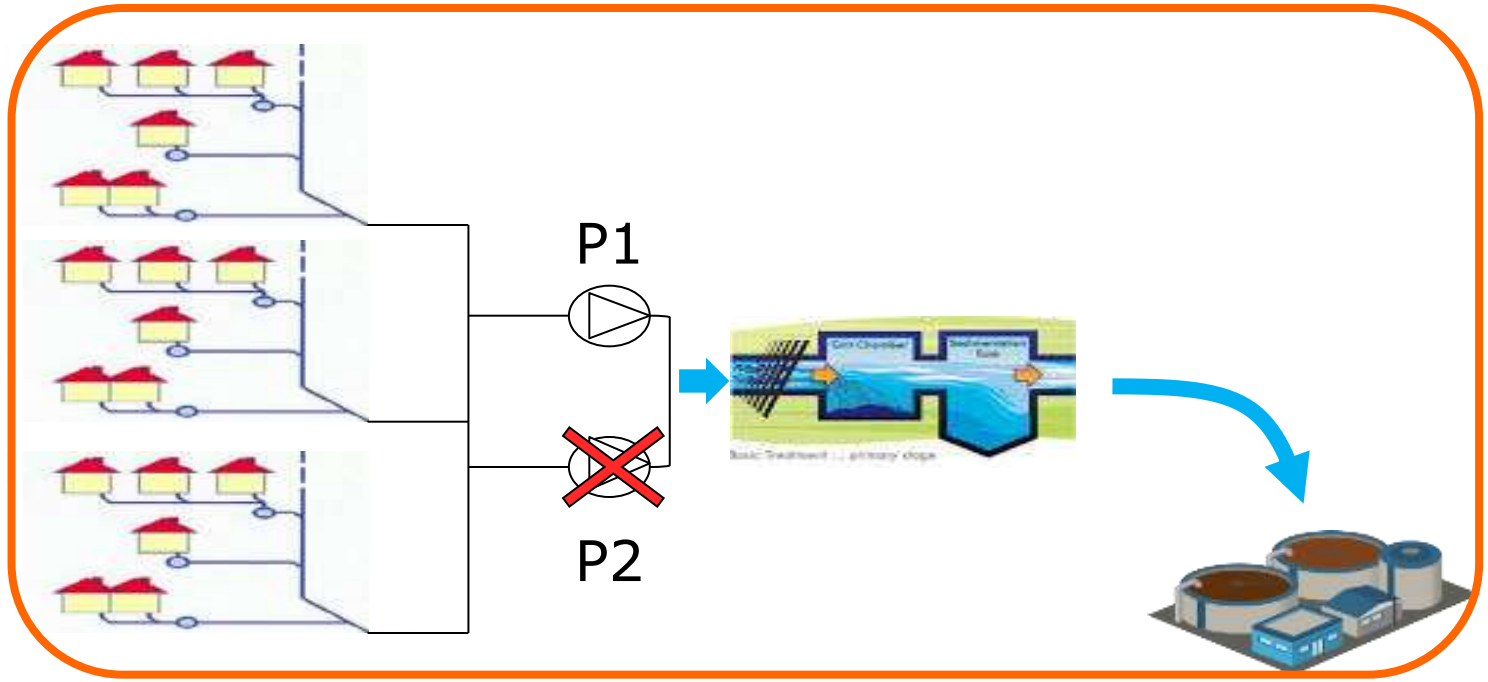




Slide courtesy of Rasmus Fogtmann Halvgaard and Julie Evald Bjerg

Controlling the WWTP based on energy prices – moving upstream

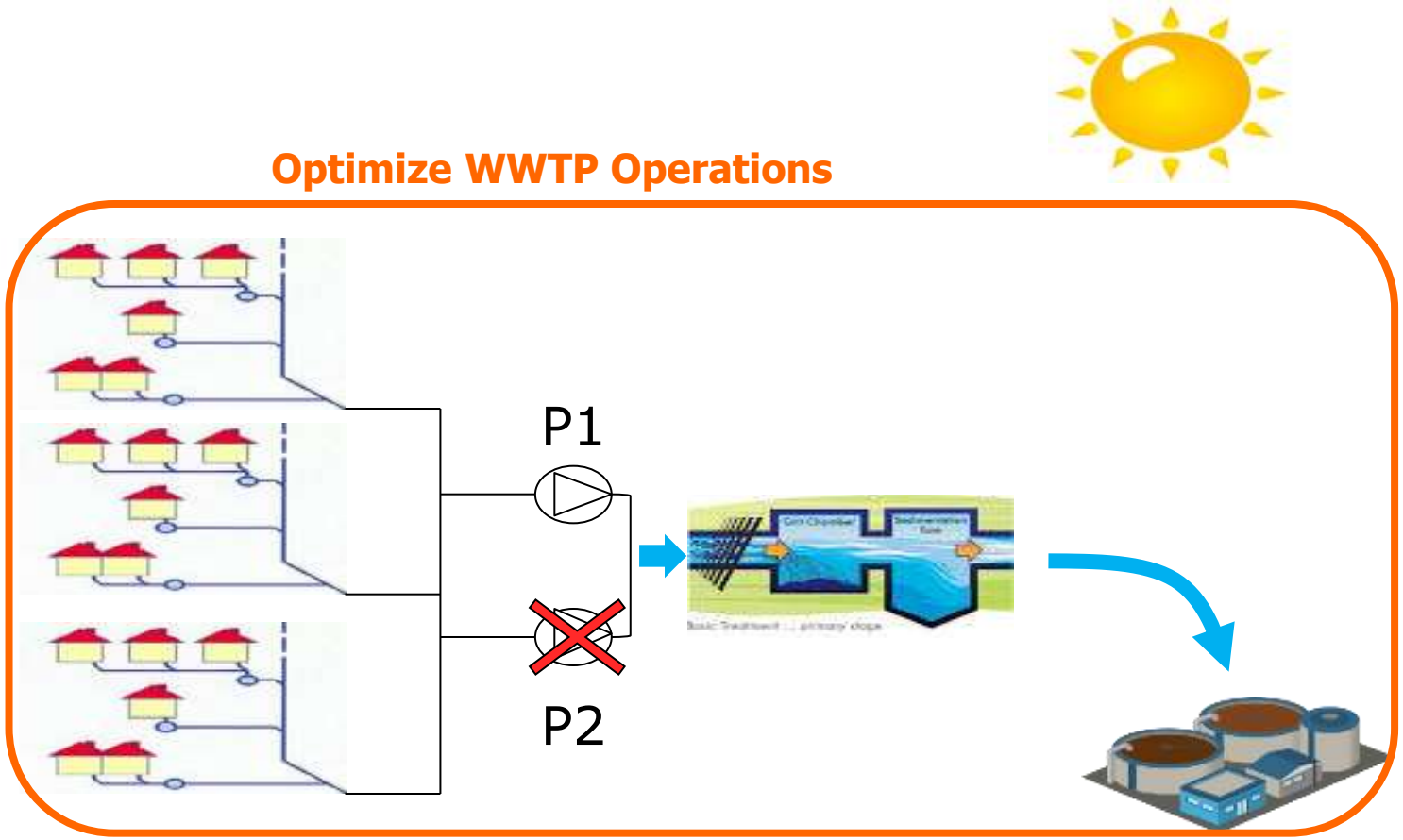




Slide courtesy of Julie Evald Bjerg and Vianney Courdant

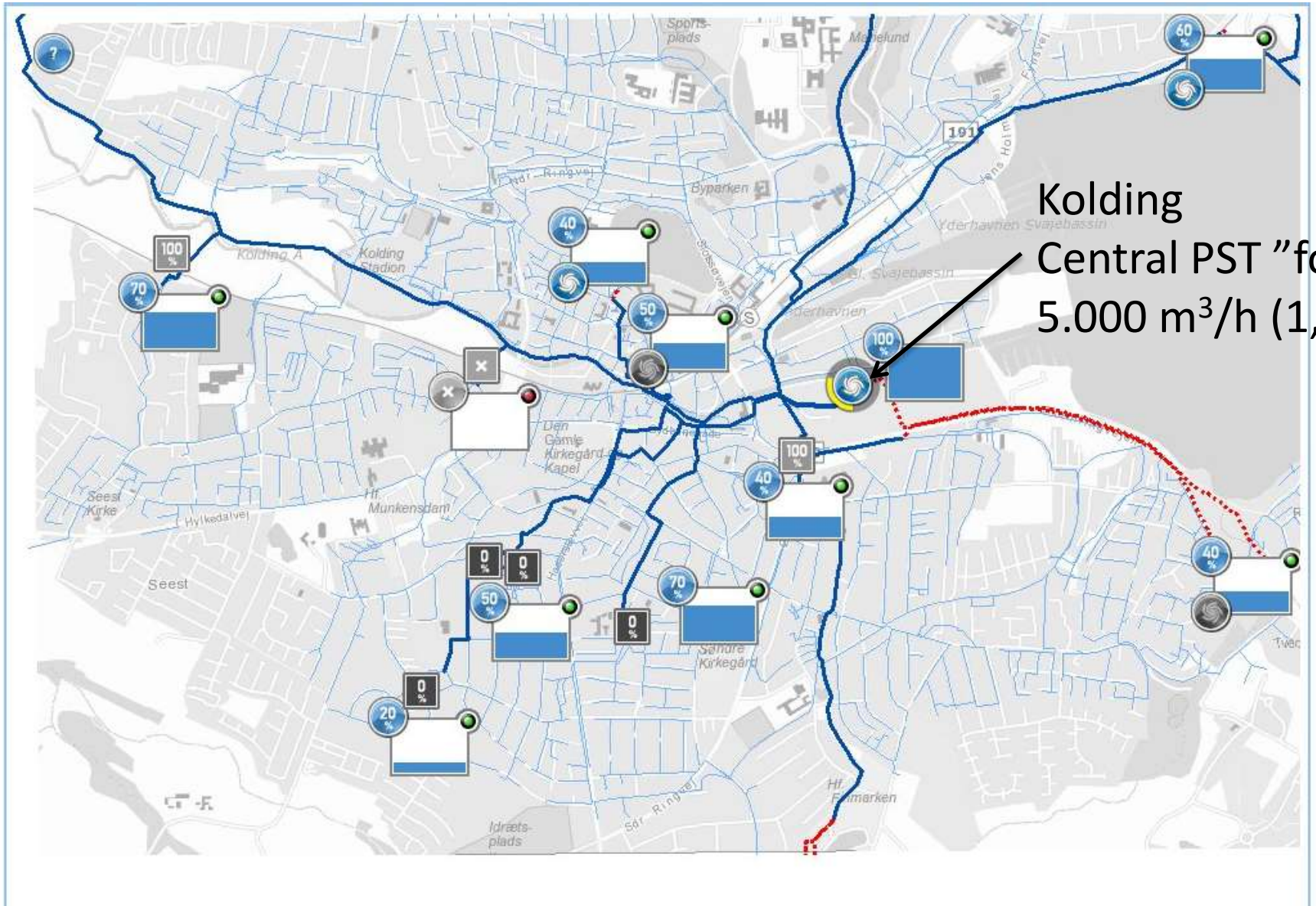
Controlling the WWTP based on energy prices – moving upstream

Numerical Weather Prediction models are used to switch between the two controls



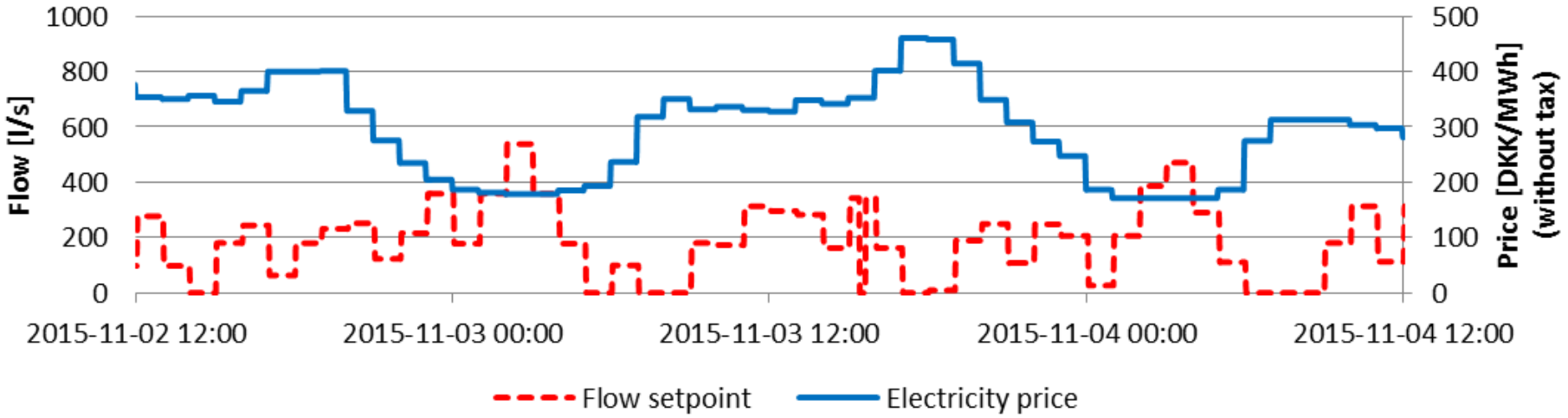
Slide courtesy of Julie Evald Bjerg and Vianney Courdant

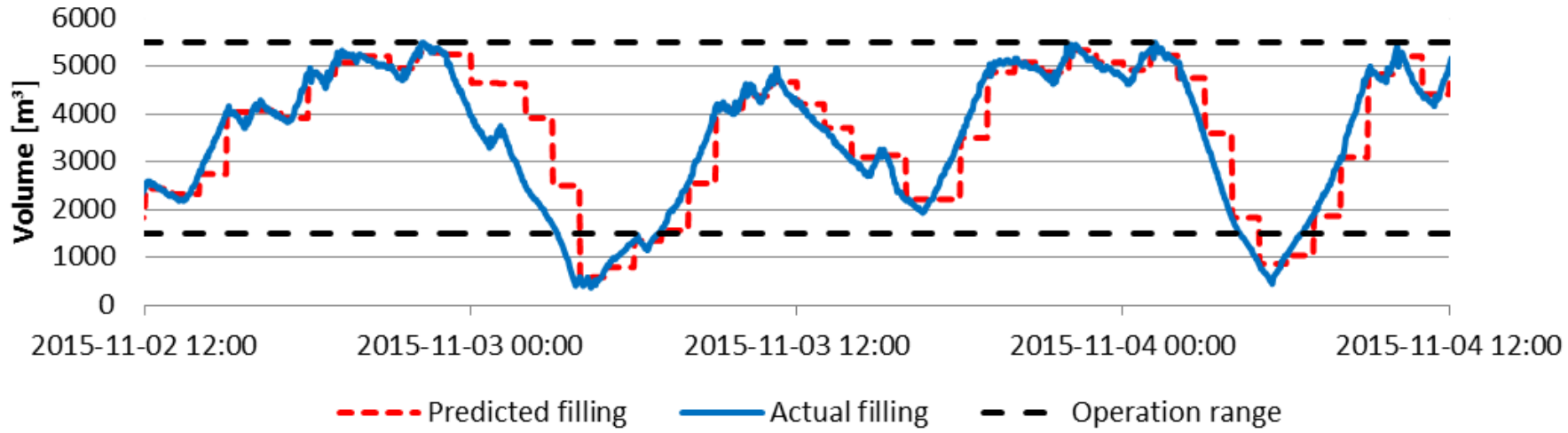
SMARTGRID in Kolding



Slide courtesy Krüger Veolia A/S

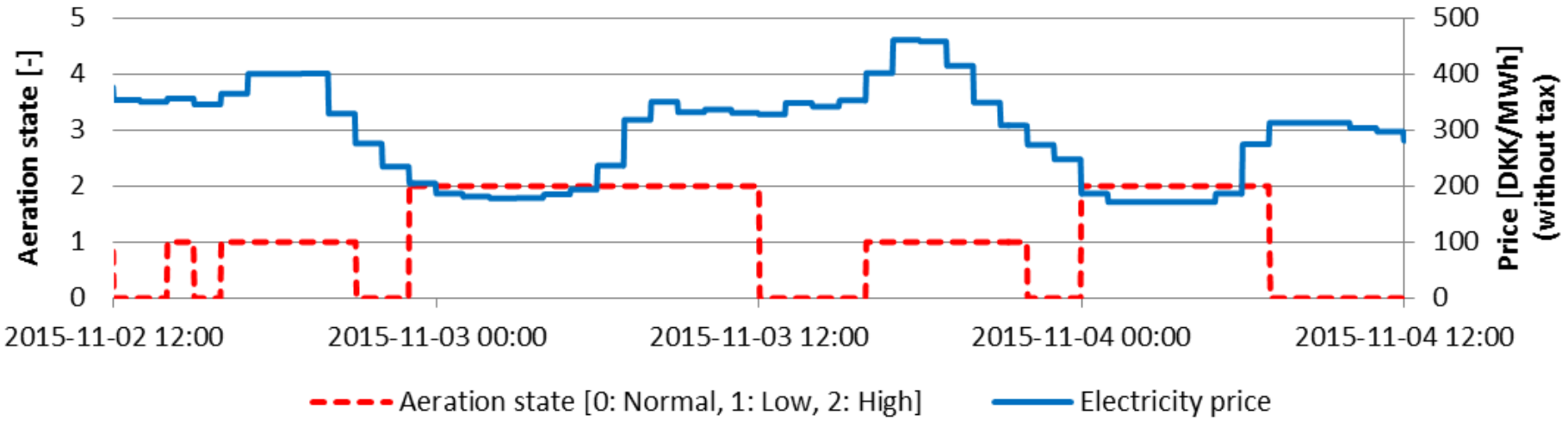
SMARTGRID in Kolding - Sewer
(3 days of full scale)

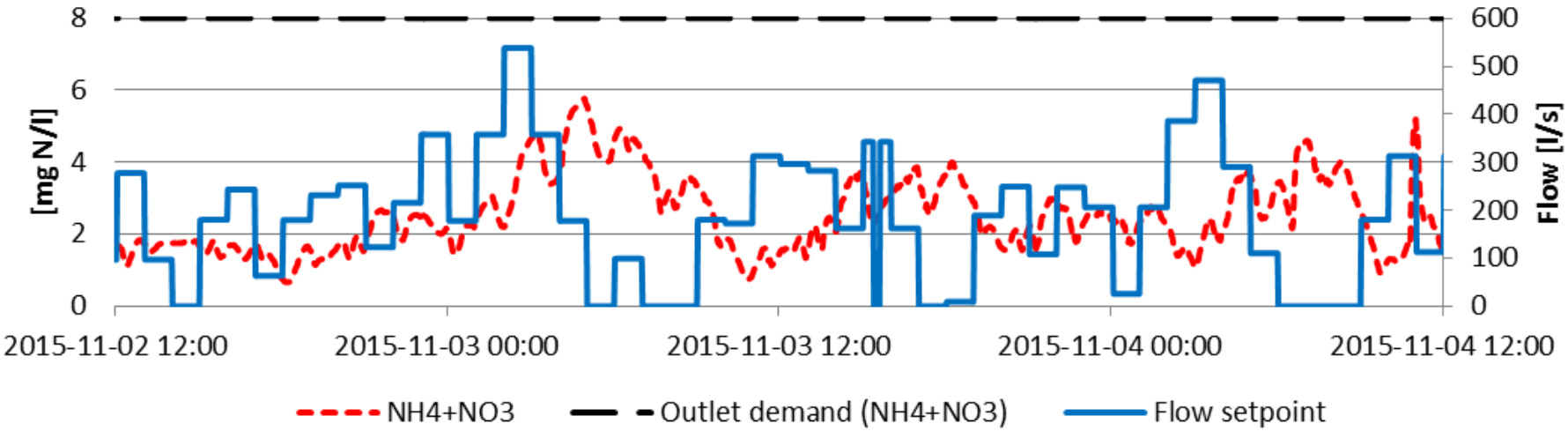




Slide courtesy Krüger Veolia A/S

SMARTGRID in Kolding – WWTP
(3 days of full scale)



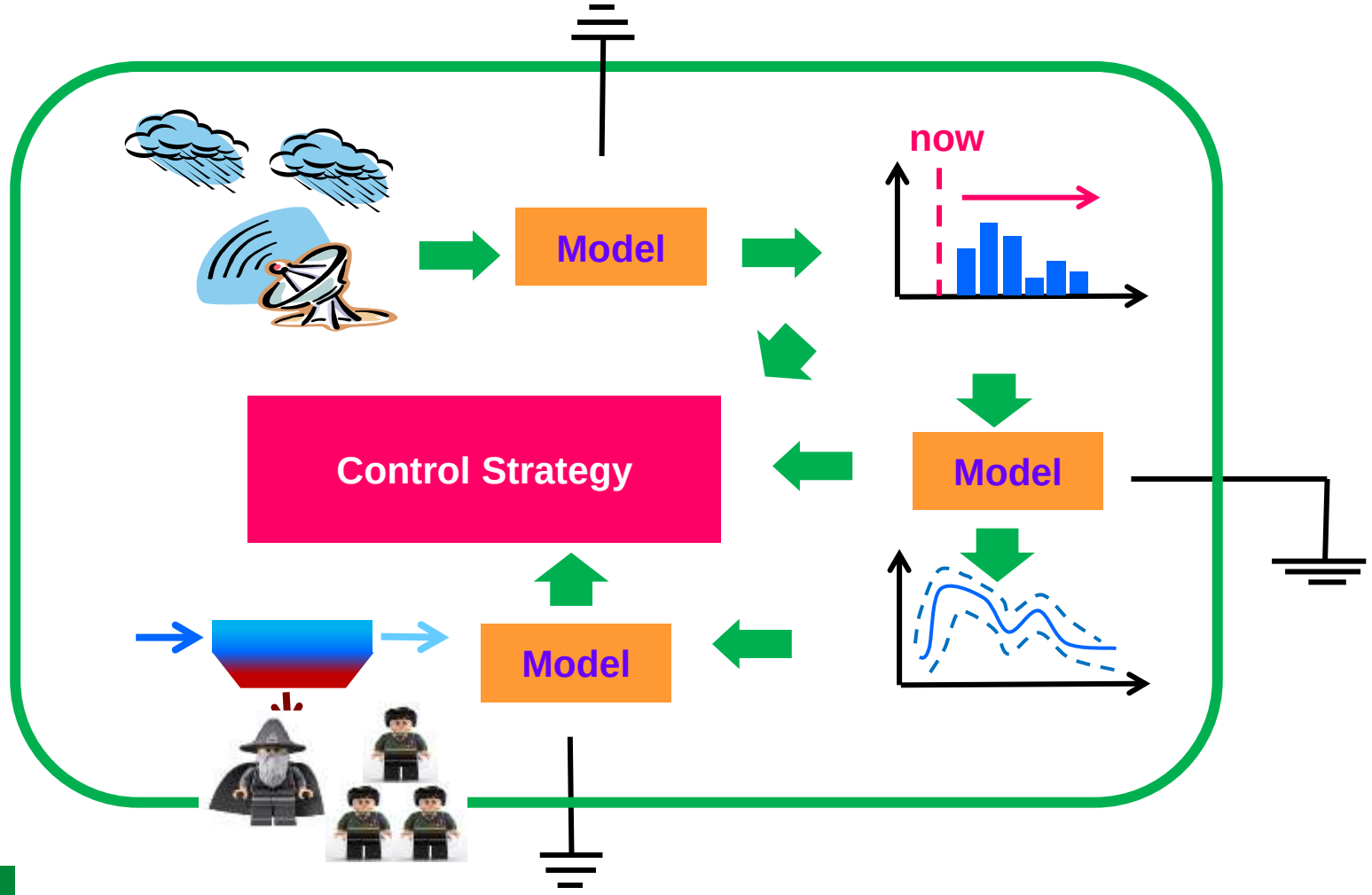


Slide courtesy Krüger Veolia A/S

The fellowship of SWI – the long journey

Measurements + Models + Forecasts + Uncertainty =

The happy operator



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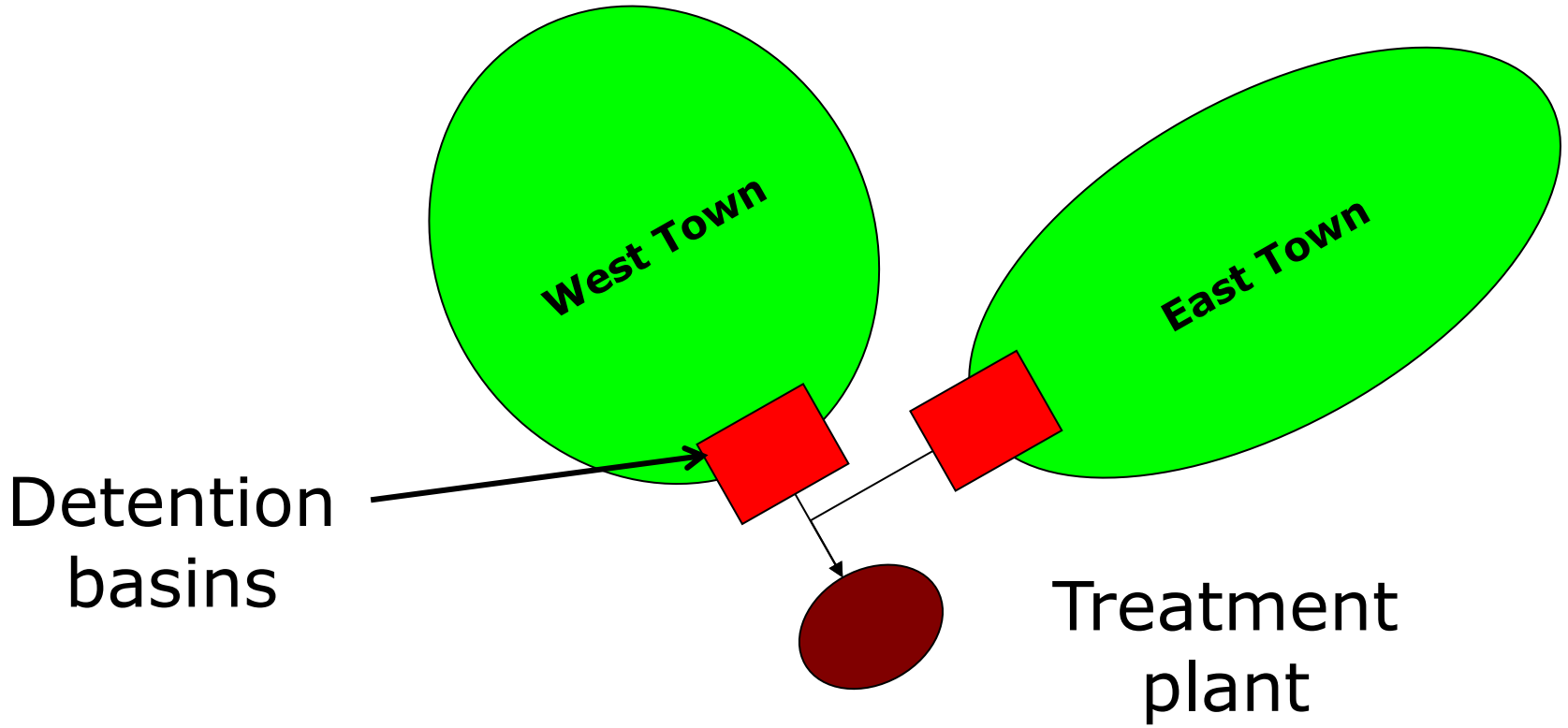
Why uncertainty matters

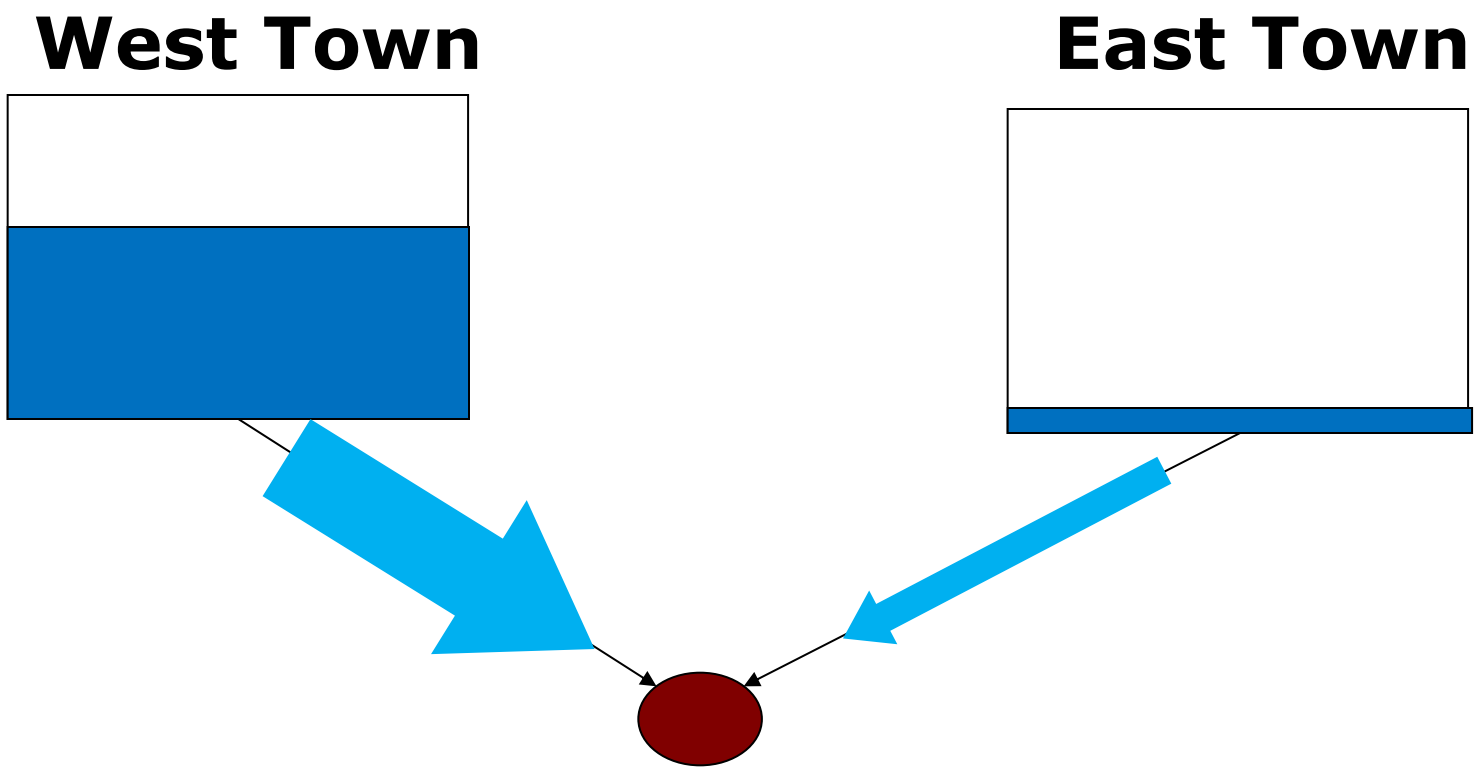
Didactical example



Real Time Control

Objective:

Maximize storage

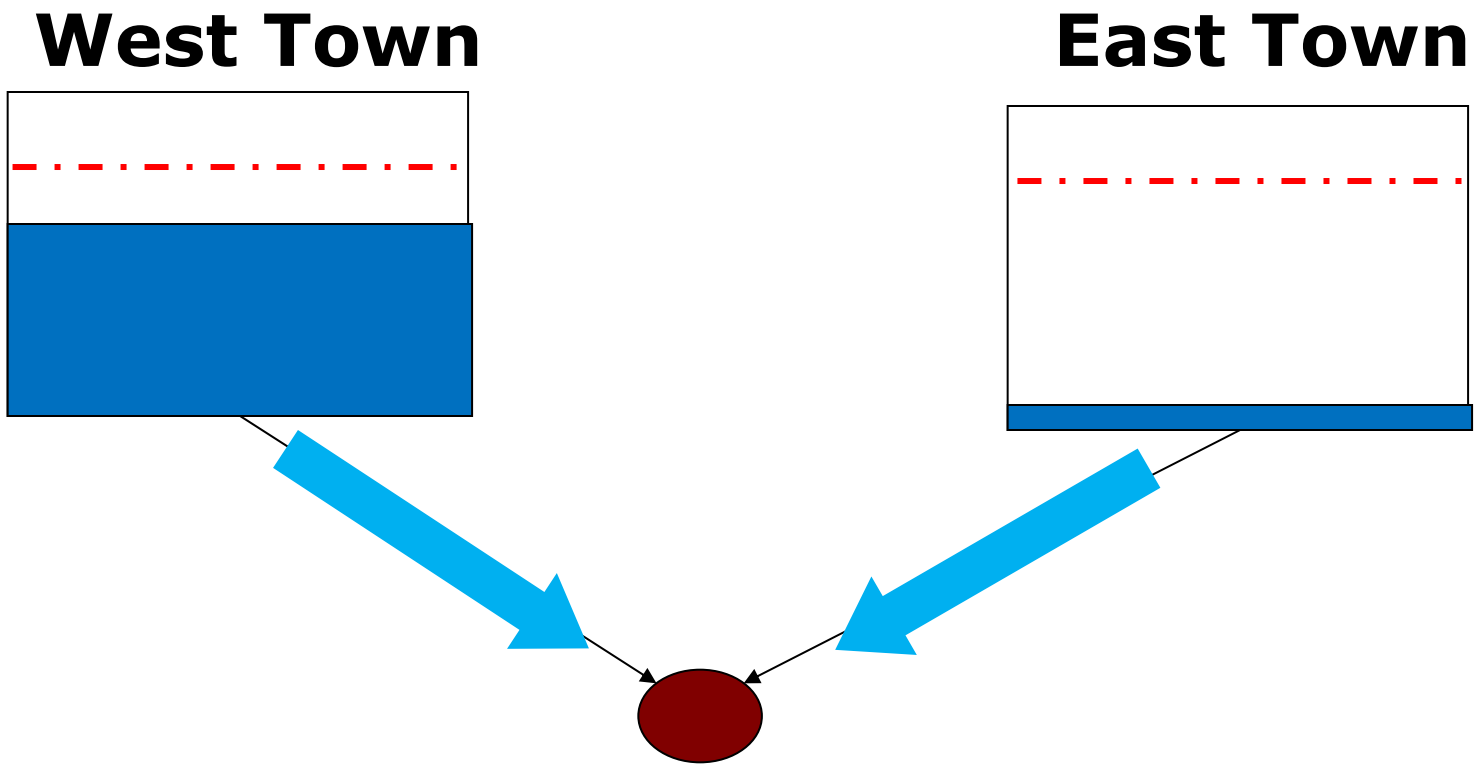


“Traditional” MPC

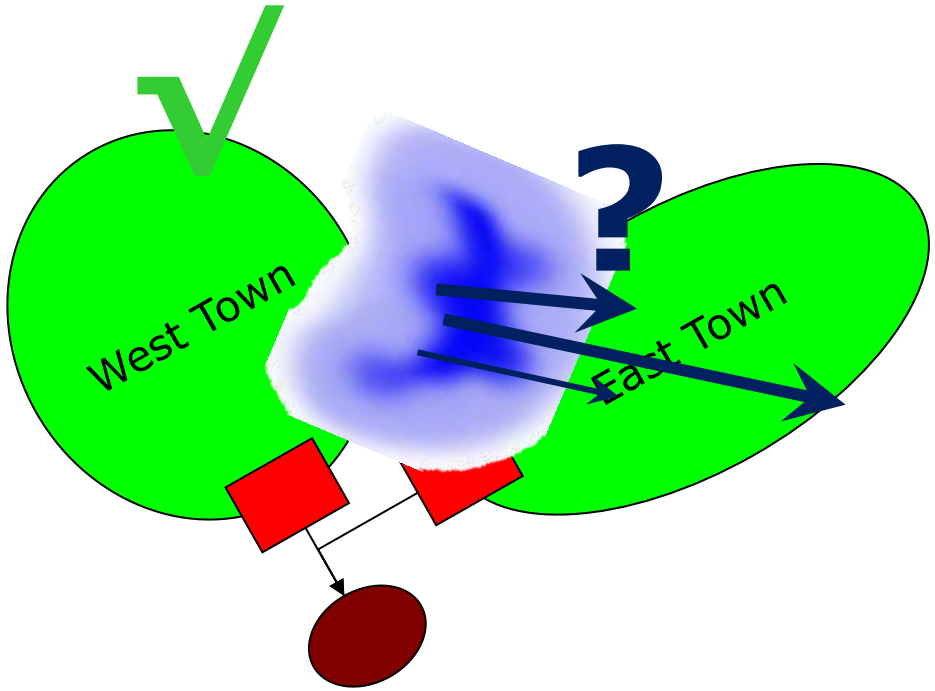
Objective:

Maximize future storage

Model forecast (without uncertainty)

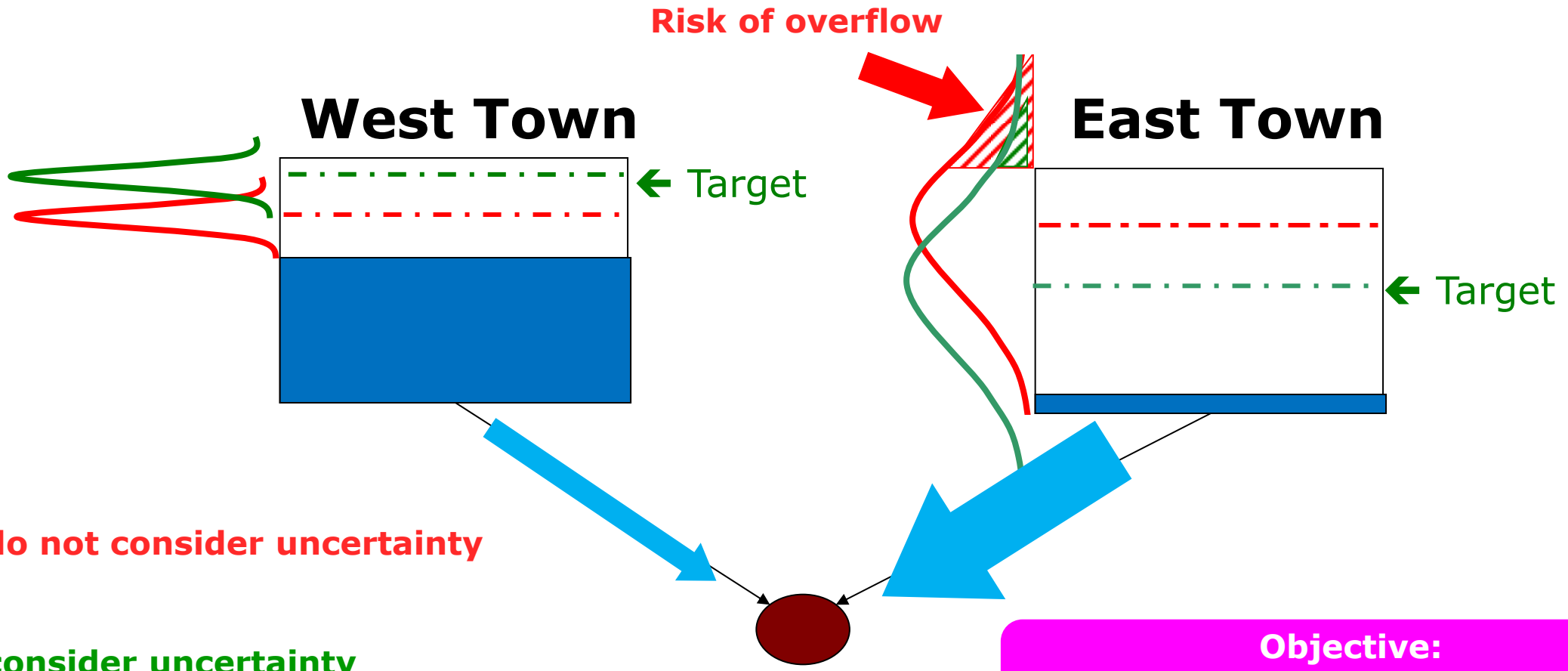


Risk-based Model Predictive Control



Rainfall evolution is uncertain

Risk-based Model Predictive Control



If we do not consider uncertainty

If we consider uncertainty

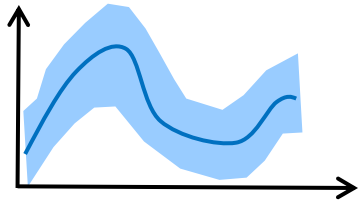
Objective:

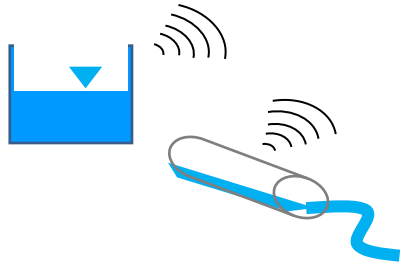
Minimize CSO risk

The Dynamic Overflow Risk Analysis (DORA)

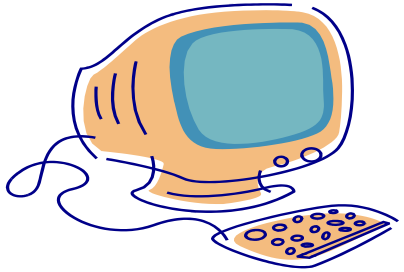
Radar-based runoff prediction

Uncertainty of forecasts





On-line data



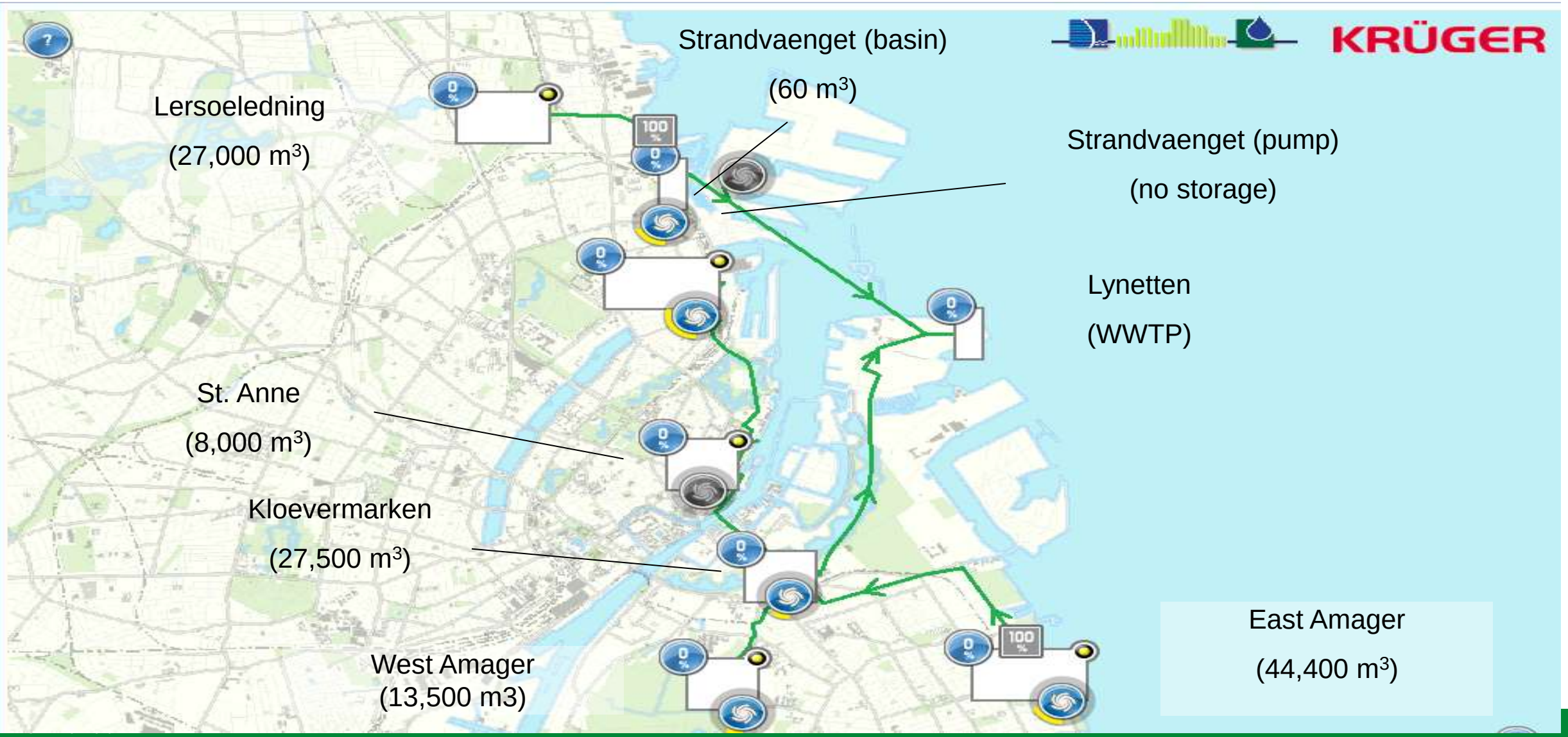
Dynamic Overflow Risk Assessment (DORA)

Optimal set-points

Vezzaro, L., & Grum, M. (2014). J. Hydrology, 515, doi:10.1016/j.jhydrol.2014.05.019.

The Lynetten catchment

Central Copenhagen, Denmark



Sensitivity of overflow recipient

CSO ”price”

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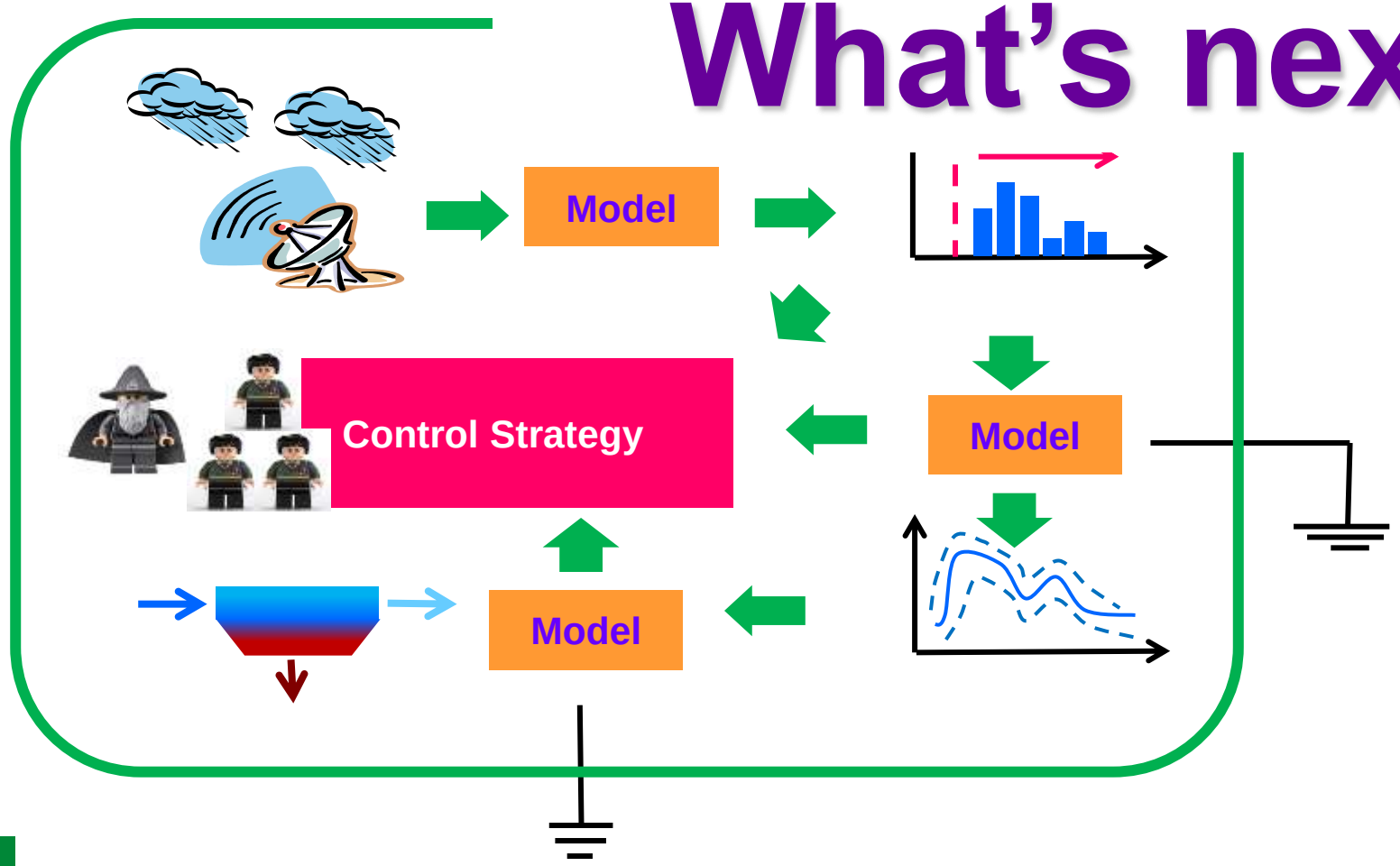
The happy operator

What's next?



neasurements

'm rainfall forecasts

- Continuously updated hydrodynamic models
- Stochastic rainfall-runoff forecast
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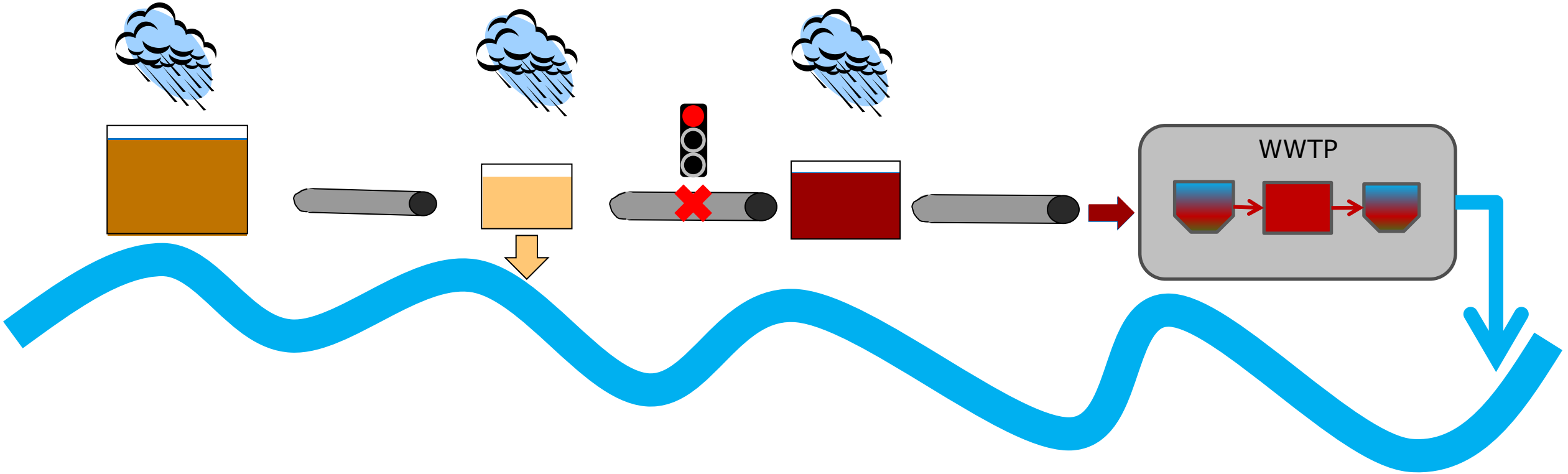
- MPC strategy addressing uncertainty

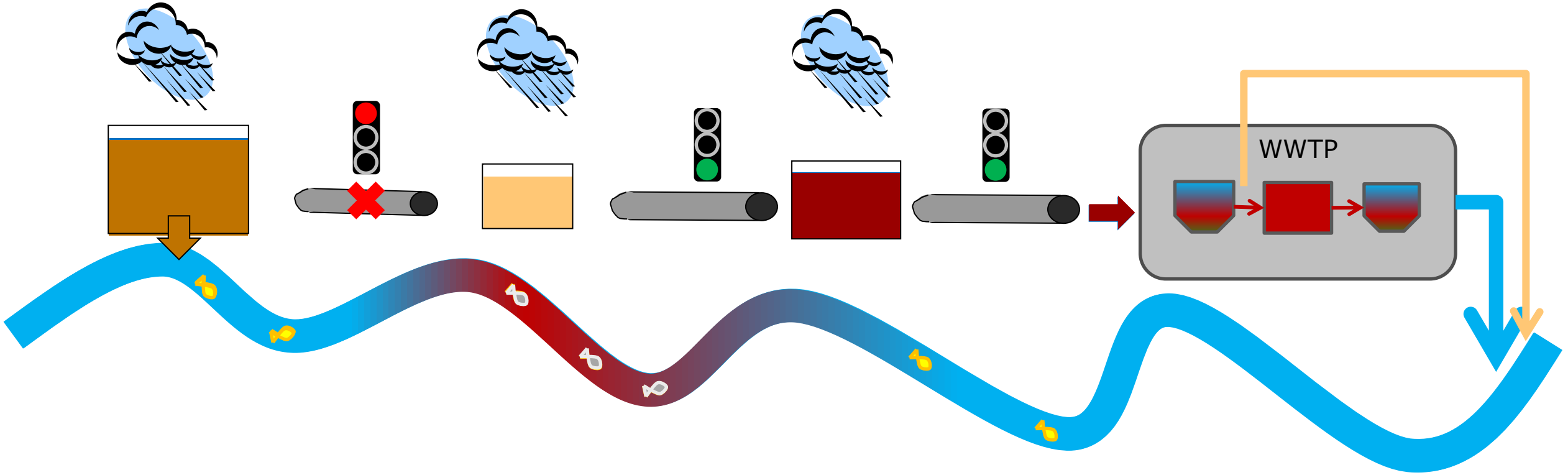
Water Quality-based control

- Pollutant concentrations are not uniform →



Water Quality-based control

- Pollutant concentrations are not uniform → we can control the system based on Water Quality (instead of water quantity)
- The natural waters have not all the same status →



On-line water quality data

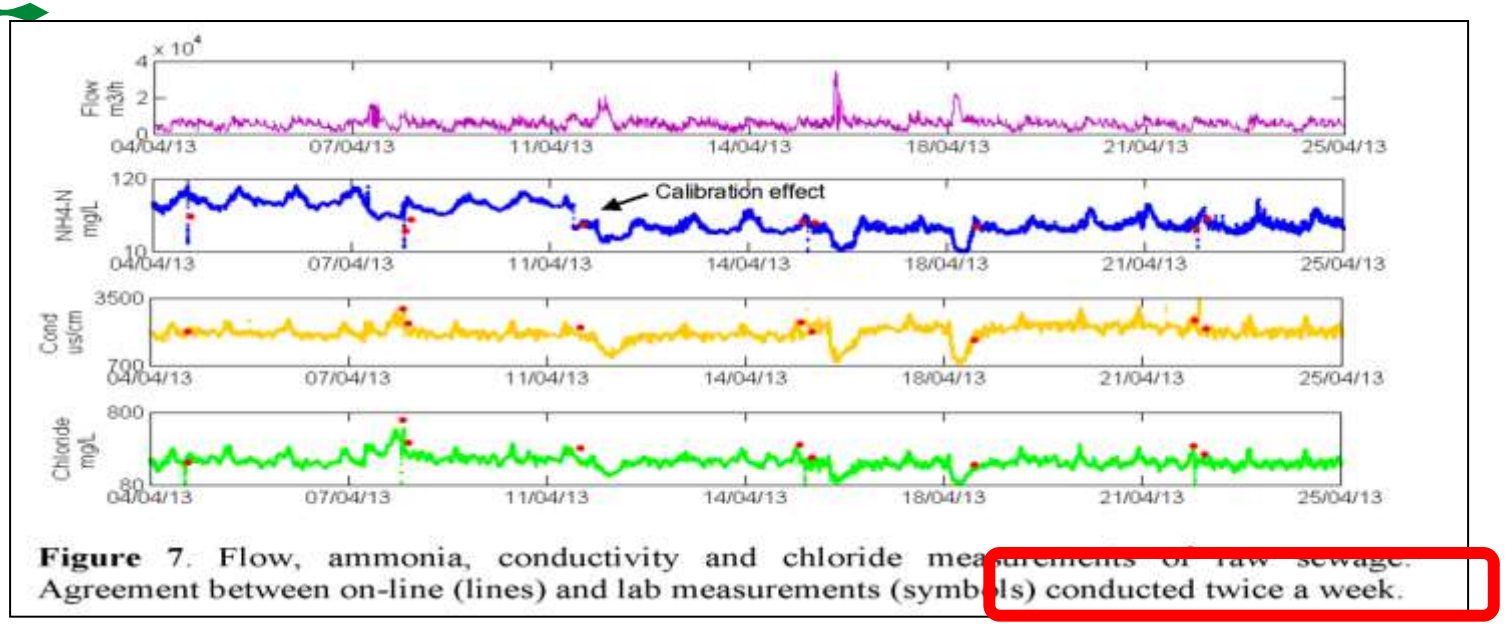


Figure 7. Flow, ammonia, conductivity and chloride measurements of raw sewage. Agreement between on-line (lines) and lab measurements (symbols) conducted twice a week.

Alferes et al. (2014), Advanced monitoring of wastewater quality: data collection and data quality assurance, Proceedings of 13th ICUD2014

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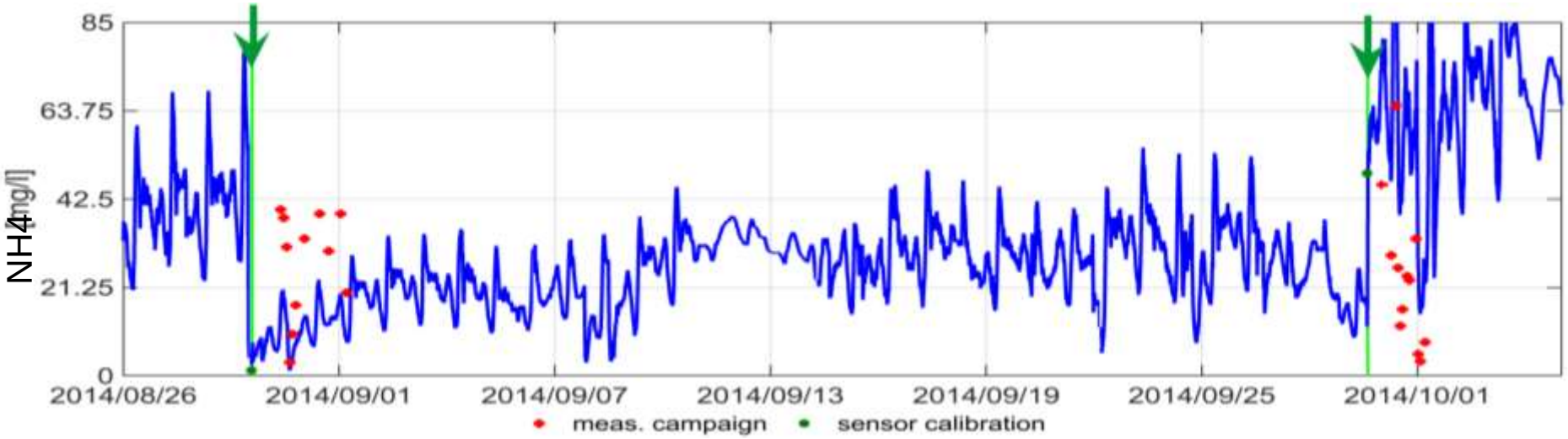


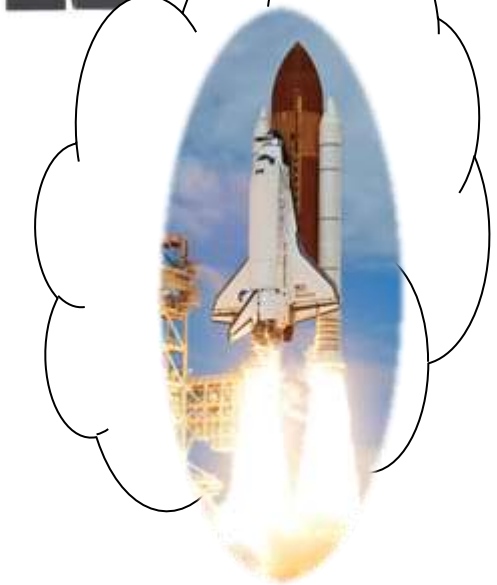
The big challenge of online water quality measurements

Photo by Linea Sofie Skov

Photo by Ravi Kumar Chhetri

Sensor
Maintenance
Multivariate DQC
Software Sensors
…

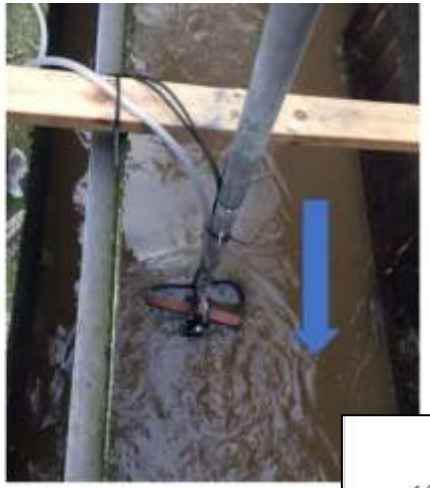
WHAT????
Which language is he/she talking?

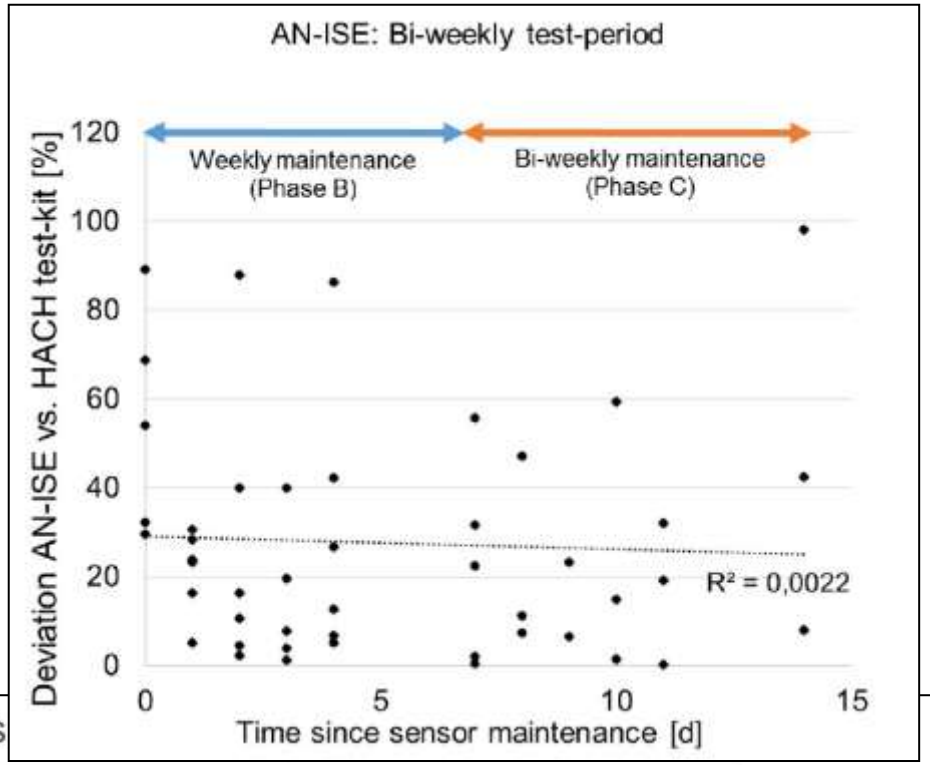


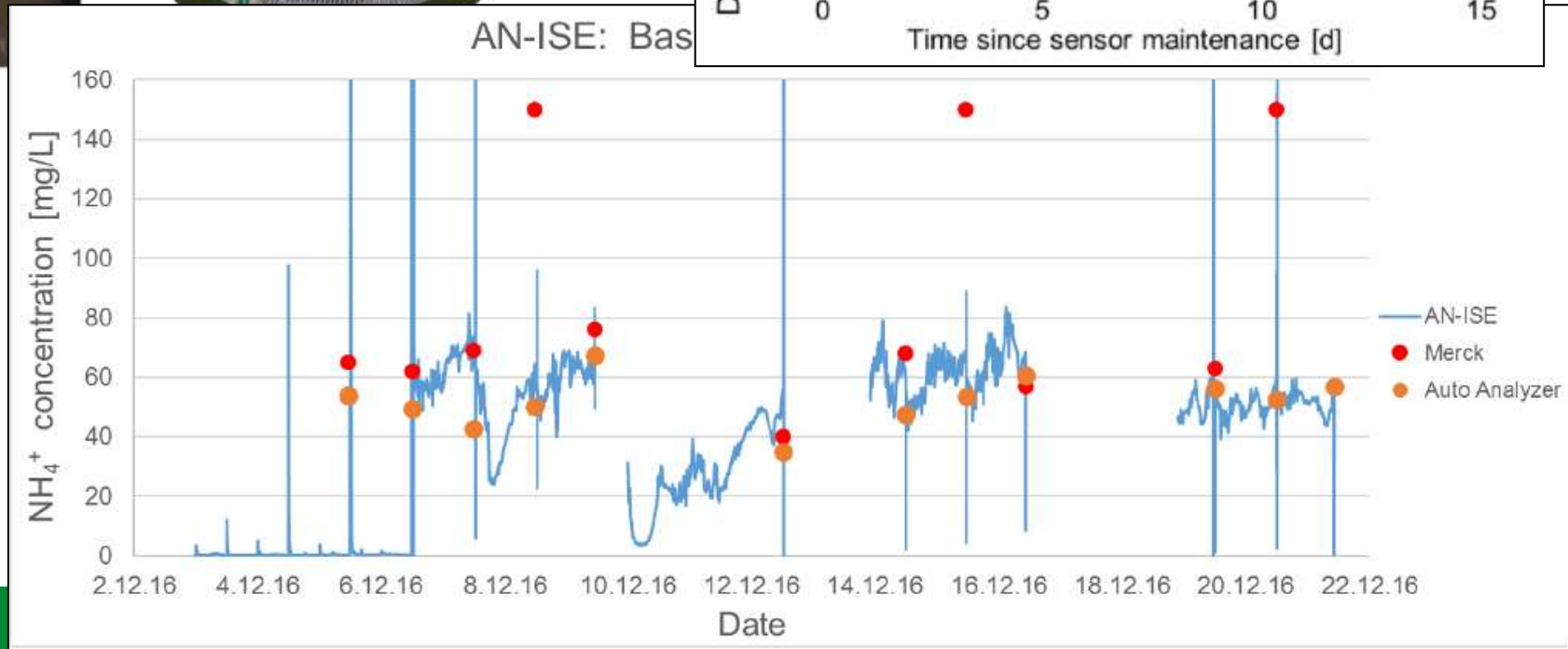
The Ålebækken ”playground”

Slide credits: Linea S. Skov

How much can we trust sensors?

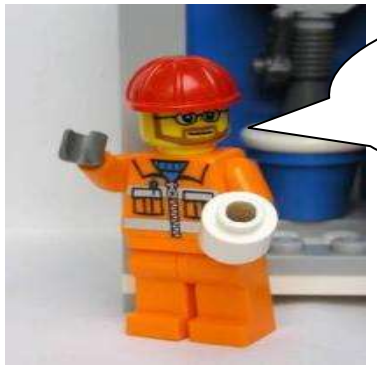






Slide credits: Linea S. Skov

The importance of involving the final users



Dear smart people from university, what wonderful tool did you prepare for me?

If you use a stochastic differential equation…

With a genetic algorithm which minimizes risks you will….

We have an Extended Kalman Filter to assimilate data and…

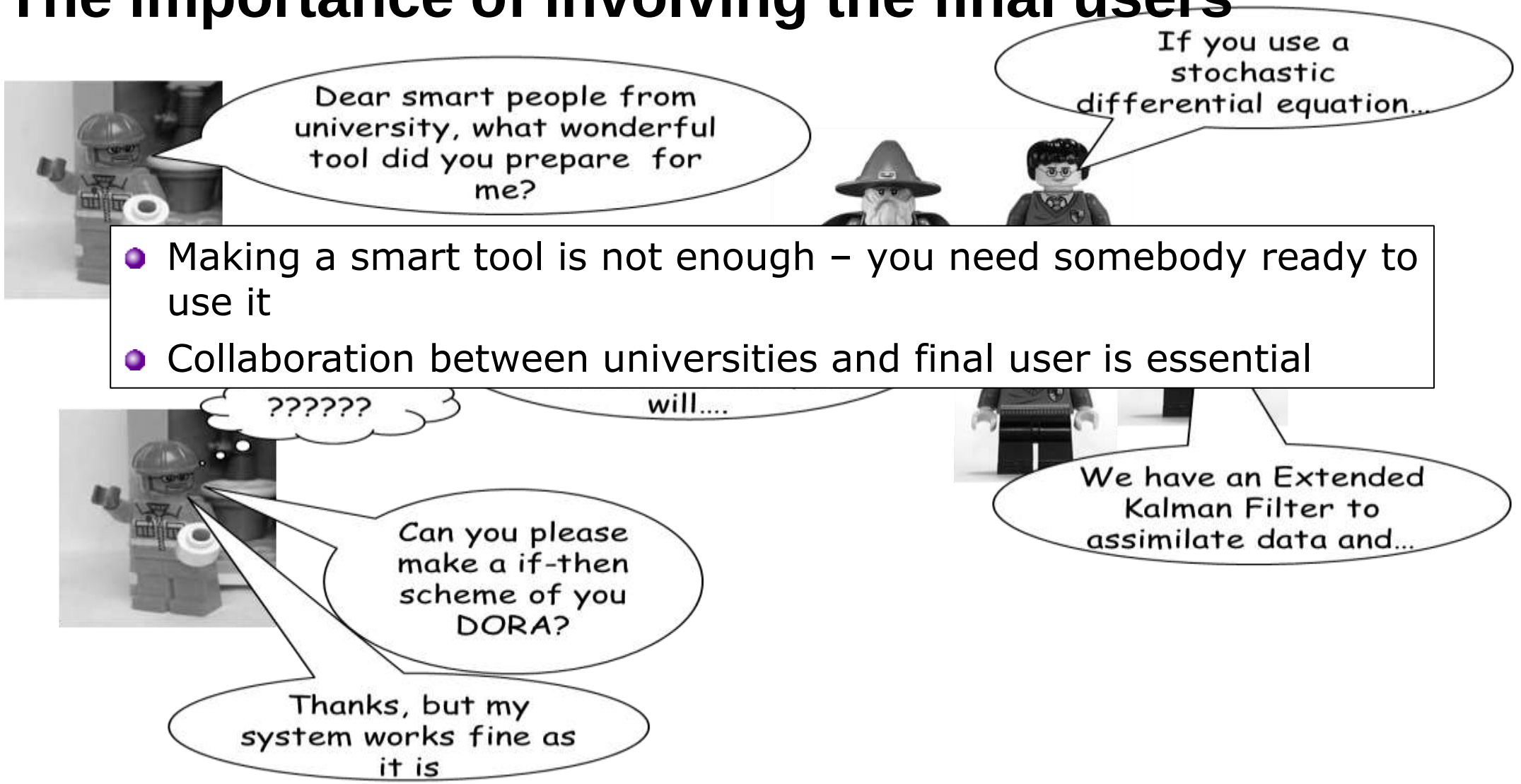
??????

Can you please make a if-then scheme of you advanced control?

Thanks, but my system works fine as it is

From lego.wikia.com

The importance of involving the final users



- Making a smart tool is not enough – you need somebody ready to use it
- Collaboration between universities and final user is essential

From lego.wikia.com

Conclusions

towards a better environment with smarter sewer systems

- We can have a better environment if we use our sewers in a smarter way
- We have now new tools for on-line model-based operation of integrated urban wastewater systems (more than 10 years of research/development)

Measurements + **Models** + **Forecasts** + **Uncertainty** =

The happy operator

Thank you for listening!

An overflow expert

luve@env.dtu.dk